University of Alberta

Projecting height growth of understory *Picea glauca* in stands with an overstory dominated by *Populus tremuloides*

By

Glenn Buckmaster

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

In

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Glenn Buckmaster
#301 - 10167 - 118 Street
Edmonton, Alberta, Canada
T5K 2M9

Date: Jan 30, 2003

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Projecting height growth of understory *Picea glauca* in stands with an overstory dominated by *Populus tremuloides*,** submitted by **Glenn Buckmaster** in partial fulfillment of the requirements for the degree of **Master of Science** in *Forest Biology and Management.*

Dr. Stephen J. Titus (supervisor)

Dr. Douglas P. Wiens

Dr. Phil G. Comeau

Dr. Mike Bokalo

Date: Jan 29, 2003

Abstract

Development of height growth projection models will assist in management of mixedwood stands. Plots were established in stands with an overstory dominated by trembling aspen (*Populus tremuloides* Michx.) and an understory with white spruce (*Picea glauca* (Moench) Voss) present.

Non-linear regression analysis was utilized to examine the relationship between understory white spruce height increment and potential individual explanatory factors. Relative crown length, breast height age, and overstory tree spacing factor showed the strongest correlation to height increment. Based on these variables a multiple regression model was built to project future height increments.

The importance of relative crown length (RCL) for predicting height increment resulted in the need for a model to predict RCL. The final RCL model included breast height age, overstory coniferous spacing factor, and deciduous spacing factor as explanatory variables. The height increment and RCL models were then jointly incorporated for use in the Mixedwood Growth Model (MGM).

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1 Introduction

1.1 Background

Until recently, western Canadian forest companies almost exclusively used the "traditional" method of clear-cut forest management. Therefore, interest in stand regeneration focused predominately on establishing commercially important species on open site monoculture plantations. This included white spruce *(Picea glauca)*, which is considered one of the more difficult species in the boreal forest to reliably regenerate (naturally) after clear-cut harvesting; therefore large expenditures are often required to ensure successful reforestation (Greene et al. 1999). However, studies suggest that white spruce will regenerate successfully in shelterwood management scenarios (Youngblood and Zasada 1991). The success of the shelterwood regeneration method is likely because it more closely replicates natural white spruce regeneration, with white spruce establishing under a deciduous canopy after a disturbance. This natural process is the reason white spruce is more often present in mixedwood rather than pure stands.

The success of regenerating white spruce is dependent on a number of factors including: seed source, forest floor substrate, soil temperature, and light transmittance (Greene et al. 1999, Delong et al. 1997, Lieffers and Stadt 1994). For white spruce there is a large variation from year to year seed production making the annual seed source available for regeneration very erratic (Greene et al. 1999). When a sufficient seed source is available, elevated positions on the forest floor (such as, rotten logs and mounded soil) provide the most successful establishment locations (Delong et al. 1997). After establishment, non-tree species such as (*Calamagrostis canadensis* (Michx.) Nutt.) can impact seedling survival by delaying thawing of soils (Hogg and Lieffers 1991). In addition, if competition vegetation is dense enough light transmission is reduced below 8% survival of white spruce becomes doubtful (Lieffers and Stadt 1994).

Although trembling aspen can negatively impact white spruce growth, it has been suggested that through the processes of competitive reduction and facilitative production, trembling aspen can improve (or minimally impede - compared to other species) understory white spruce establishment and growth (Man and Lieffers 1999). Competitive reduction is when two species do not vigorously compete for a given resource in the same niche, an example of this when overstory trembling aspen and understory white spruce compete for light resources. Overstory

aspen will transmit significantly more light than overstory white spruce (14% to 40% for aspen versus less than 10% for spruce - Lieffers and Stadt 1994). Therefore, as spruce height growth dramatically decreases at light transmittance levels less than 40% (Wright et al. 1998), white spruce will grow faster under an aspen canopy than under a white spruce canopy. Facilitative production occurs when two species interact so that the growth of one (or both) is promoted by the other species. Two examples of how overstory trembling aspen can help the growth of understory white spruce are by moderating environmental extremes and by controlling the density of competitors (Man and Lieffers 1999).

In Alberta, a typical mixedwood stand has a mixture of trembling aspen (*Populus tremuloides*) and white spruce (*Picea glauca*). There is some evidence of greater overall yield in mixed stands compared to pure stands of similar condition. In stands from 48 to 105 years old, the mixed portion of a stand has been shown to have 10% greater total biomass along with 10.5% greater periodic annual increment (PAI) over the pure aspen portions of the same stand (MacPherson et al. 2001). Although not as clearly understood, there is also some evidence that mixed stand yield will exceed that of pure white spruce stands when a two-stage harvesting system is used (Man and Lieffers 1999).

This ability for aspen and spruce to grow well together in addition to aspen being commercially important and a large area of the boreal forest being covered by mixedwood stands, has increased interest in mixedwood management. As more of western Canada's forests become managed under a mixedwood regime, it will be important for foresters to understand the interaction between these tree species. This study attempts to add to this knowledge, by focusing on the growth of white spruce under a trembling aspen (or secondarily balsam poplar – *Populus balsamifera*) dominated canopy.

1.2 Objectives

The 3 main objectives of this project are:

1. To quantify the relationship between understory spruce height growth and overstory variables like crown closure, light transmittance, tree spacing factor, and density (trees/ha).
2. To use this information to produce a predictive growth equation that can be incorporated into the Mixedwood Growth Model (MGM).

3. To make a preliminary assessment of the understory spruce mortality experienced in the sampled stands.

These objectives are achieved in this thesis by first outlining the location and methodology of the field sampling process. Next, the results and discussion section describe in detail the building of a height increment model for both understory spruce taller than 1.3m and understory spruce less than and equal to 1.3m. Due to the importance of relative crown length in formulating the height increment equations and to enable the broadest possible use of those equations, a model predicting relative crown length was also produced. The results and discussion are then followed by concluding statements and recommendations for future studies.

Included in the appendices are several sections which discuss areas of secondary importance like: preliminary results from MGM, preliminary assessment of mortality, detailed descriptions on variable measurement, characteristics of sampled stands, field sampling quality control, and SAS programs that were utilized during this study.

2 Methods

2.1 Project data

At project commencement, two potential sources of data were identified: field sampling and data sets from related projects. However, after a review of available data sets it was determined that only the project-collected data would be analyzed. Concerns over differences in methods, measurement standards, overall design, time, and location, made using other data sources impractical.

The field data for the project was obtained from two separate general locations – the Central Mixedwood sub-region of the Boreal Forest natural region (to be referred to as "Boreal sub-region" for the remainder of the report) and the Lower Foothills sub-region of the Foothills natural region. Sampling for the Boreal sub-region took place in two, forest management units (FMUs); L1 located just north east of the town of Lac La Biche and L2 located north of the town of Athabasca. Sampling for the lower foothills sub-region was in W6 (FMU) just north of the town of Cynthia (south east of Edson) Figure 2.1).

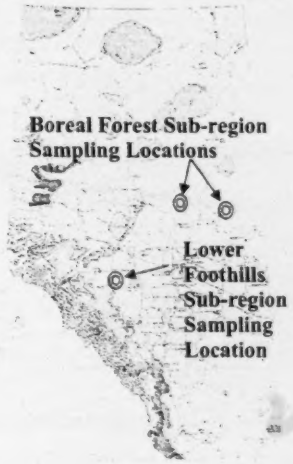

Figure 2.1 Project Sampling Locations (source - Alberta Environment - Huang et al. 1994)

2.2 Stand identification and stratification

The goal of field sampling was to locate plots in stands where white spruce was growing under a predominately trembling aspen canopy (or trembling aspen + balsam poplar – in the Lower Foothills sub-region). To ensure cost and time effectiveness the Alberta Vegetation Inventory (AVI) was used to quickly identify and locate stands that fit the desired sampling criteria.

A stand was deemed eligible for sampling if the following criteria were met:

- AVI stand description indicated greater than 80% trembling aspen (trembling aspen + balsam popular in the Lower Foothills sub-region) composition in the overstory and white spruce being either the first, second, or third most common species in the understory
- The stand could not have been impacted by external factors that would affect growth (i.e. fertilization)
- The stand was accessible by ATV. Any potential bias caused by this criterion should be minimal because the majority of stands in the sampling locations were accessible due to a network of roads and seismic lines.

In mixedwood stands understory spruce growth is affected by overstory removal and vegetation control (Groot 1999). Therefore, it was deemed important that the final stands selected for sampling represent a range of overstory competition levels. AVI stand crown closure calls were used to provide an initial estimate of overstory competition.

As well, the term "understory white spruce" can refer to a wide range of tree sizes (i.e. from a 3cm emerging seedling to a tree 12m+ in height that has not reached the main canopy). It is reasonable to expect these different sized trees to react differently to similar environmental impacts and to be influenced by different stand attributes (i.e. *Calamagrostis canadensis* usually provides little or no competition to a 5m tall spruce, but is a significant competitor to a 50cm spruce). This made it important to sample a variety of different sized understory white spruce trees. Therefore, AVI understory height calls were used to group stands by understory spruce heights.

Stands identified as eligible for sampling were grouped into the following 25% overstory crown closure classes and 5m understory spruce height classes:

Understory white spruce height (from AVI)

- 0 - 5m
- 5.01m - 10m
- 10.01m - 15m

Overstory crown closure (from AVI)

- 0 - 25%
- 26% - 50%
- 51% - 75%
- 76% - 100%

Ecological sub-region

- Lower foothills
- Boreal

This resulted in eligible sampling stands being placed in one of 24 sampling strata (12 for each sub-region). This stratification process was completely dependent on the accuracy of AVI stand calls. Due to AVI data being collected from aerial photography, overstory information is considered to be more reliable then understory data. Therefore, in the context of this study, overstory crown closure calls were expected to be accurate, while understory height calls were expected to be an approximation only. In addition, it is expected that the understory white spruce component of some stands will have not been visible from aerial photographs (due to high overstory density, very sparse spruce density, or spruce small in size) and thus not recorded in AVI. Regardless of these issues, the results should not be significantly impacted because the analysis was based on the values measured at the plot and was not tied in any way to AVI. Furthermore, the stratification process was used only as an attempt to sample across the range of variability and did not impact how the analysis was carried out.

2.3 Stand selection and plot establishment

Stands were randomly selected for sampling from every stratification class and where possible, an equal number of stands were sampled from each category. However, due to time constraints and difficultly locating some plot types this was not always feasible.

Plots were randomly located within a stand by placing a 40m x 40m grid over the stand and sequentially assigning a number to each grid box. Then, a random number was selected to determine the grid box that the plot cluster would be located in.

Field sampling was carried out from mid-July to early-September 2000. Each selected stand was sampled using a cluster of three circular $100m^2$ fixed area plots (both overstory and understory

measurements taken within the same plot), placed 30m apart forming an equilateral triangle (Figure 2.2). Each plot centre was marked with a metal post and tagged for later quality control (appendix 6.9). This plot format was chosen for the following reasons:

1. The distance of 30m was thought to be a good compromise between having the plots close together to enable faster sampling and yet enough distance to ensure plots are located in a different part of the stand.
2. The consistent plot cluster form used for each plot, reduces opportunity for biasing plot locations and allows for easy quality control.
3. The shape reduced the possibility of crossing stand boundaries in the field
4. The $100m^2$ (0.01ha) fixed area plots were selected in an attempt to average 25–30 understory spruce sampled per plot cluster (or 8 to 10 per plot).

The average number of understory white spruce sampled in the $100m^2$ plots was 25 in the lower foothills sub-region and 13 in the Boreal sub-region, which was significantly greater than intended 8 to 10 average. Therefore due to time constraints the fixed area plots were reduced to $50m^2$ (0.005ha), resulting in an average number of understory white spruce sampled per plot of 10 in the Lower Foothills sub-region and surprisingly an average of 14 in the Boreal sub-region.

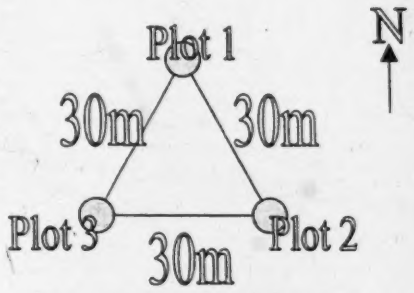

Figure 2.2 Plot Cluster Lay-Out

In the Boreal sub-region, this process resulted in a total of at least three stands sampled in each stratification class for a total of 53 stands and 159 plots. In the Lower Foothills sub-region a total of 24 stands and 72 plots were sampled. However, one sampled stand (E1) was removed from the analysis because the plots were taken in a thicket with an extreme density of 201 understory trees (average height approximately 2m) and 57 overstory trees (average height approximately 8m) in a 100m plot. Comparatively, only 655 understory white spruce were sampled in the remaining 23 stands combined. As individual height growth models were built based on this data, the stunted growth observed in stand E1 would have had an over-powering (and unrealistic) influence on the results. The final sample size for the Lower Foothills sub-region was 23 stands and 69 plots (Table 2.1).

Table 2.1 Frequency of stands sampled by stratification classification

Boreal sub-region	**Understory White Spruce Height (m)**		
Overstory Crown Closure (%)	0 to 5	5.1 to 10	10.1 to 15
0 to 25	4	5	4
26 to 50	4	5	5
51 to 75	3	5	5
76 to 100	5	4	4
Lower Foothills sub-region	**Understory White Spruce Height (m)**		
Overstory Crown Closure (%)	0 to 5	5.1 to 10	10.1 to 15
0 to 25	2	1*	3
26 to 50	0	2	1
51 to 75	2	4	2
76 to 100	4	2	0

* - One plot cluster was removed due to being a non-typical sample.

2.4 Variables measured

Measurements were taken with plot level variables being recorded first, followed by all individual overstory and understory tree attributes. For a detailed description of the field sampling procedure see appendix 7.9.

Variables in five categories were measured or derived:

1. Plot level variables – attributes directly measured at the plot level (Table 2.2).
2. Overstory Tree Variables – attributes directly measured on individual sampled overstory trees (Table 2.3).
3. Understory Tree Variables – attributes directly measured on individual sampled understory trees (Table 2.4).
4. Derived Plot Variables – plot level attributes not directly measured but calculated from directly measured plot variables (Table 2.5).
5. Derived Individual Understory White Spruce Variables – attributes from individual understory white spruce not directly measured but calculated from directly measured variables (Table 2.6).

Height increment measurements

Height increment of white spruce was based on the average over the last three years of height growth rather than a single year. The rationale for this was because in the absence of a disturbance, plant communities tend to undergo change gradually (DeGrandpre et. al, 2000). Of

the stands sampled, the most recent recorded disturbance occurred in 1989; therefore it was assumed that three years prior to the sampling date each stand was essentially unchanged. Another factor was that the climate and precipitation experienced on all sampled plots (within a sampling region) was expected to be generally the same in a single given year (due to similar geographical locations); however, it was possible (and likely) that year-to-year climate differences could be significantly different. Therefore, single year height increments are more reflective of understory spruce growth in a specific year rather than an average growth (which is far more useful when formulating predictive models). For example, if measurements took place in a year that was far wetter than average, the normally more productive stands that are moister and have richer nutrient levels may experience significantly lower growth due to flooding.

Competition Variables

In this study numerous competition variables were sampled and calculated. The purpose of these variables was to understand if there was one variable that strongly indicated the competition experienced by understory white spruce. There is a multitude of variables and indices that could have been used to measure competition experienced by an individual tree (Ledermann and Stage 2001, Tome and Burkhart 1989). However, the focus of the study was to assess potential individual tree growth based on simple stand characteristics that would be relatively simple to include in a growth model and would also be easily identifiable in the field. Therefore individual tree competition indices were deemed too unwieldy for the purposes of this study.

It was decided that commonly used and understood stand level competition variables (such as: density, basal area, and crown closure) would be the most useful for the purposes of this study. The only competition variable selected that is not as commonly used is tree spacing factor (SF) (Table 2.5). It was included for two reasons: firstly, MGM already utilizes SF making its inclusion simple; and secondly, SF is a simple variable that estimates competition levels based on tree height and density levels which is useful in this study were a wide range of stand ages and heights were sampled.

Site index

Site index is a method for estimating site quality that compares height growth of free-growing trees over time. It is based on the general understanding that height growth is correlated to site quality but is not sensitive to density levels (Davis and Johnson, 1987).

Stand site index is estimated by measuring the height and age of the site trees showing qualities of being the best competitors for resources (such as light, moisture, and nutrients). These "best competitors" are called site trees and are defined in this study as Dominant or Co-dominant trees with little or no visible damage.

When possible a site index (SI) value was assigned to each stand sampled during this project. As all the stands were deciduous dominated (in the overstory), it was difficult to find suitable white spruce site trees. Therefore, in the Boreal sub-region, only 39 of the 53 stands sampled had a white spruce site index estimate, and in the Lower Foothills sub-region only 11 of the 23 stands sampled had a site index estimate. When site index estimation was possible, the Alberta sub-region model developed by Huang, Titus and Klappstein, (1997) was used (see coding in section 7.9).

Diffuse non-interceptance light transmittance (DIFN)

Light is a potential major limiting factor influencing understory white spruce vigor (Lieffers et al. 1996). Light conditions were estimated at each plot centre by measuring the diffuse non-interceptance light transmittance (DIFN). When correctly measured DIFN provides reasonable estimates of average growing-season light conditions available to the understory (Comeau et al. 1998).

DIFN was collected using an LAI 2000 (Li-Cor, Inc. 1992), a tool commonly used to analyze light conditions (for detailed information on DIFN calculation see Appendix 7.4). However, for this study the results must be viewed with caution because measurements were not taken in "ideal" situations. Potential problems include:

- For most plots (61 of 66 plots in the boreal sub-region and 46 of 51 plots in the lower foothills sub-region) light transmittance measurements were taken during only one point

in the day. This single set of measurements may not be representative of the average light transmitted to the understory as the position of the sun changes during the day.

- Light transmittance was only taken at plot centre. Although it is expected that plot DIFN measurements would be relatively close to the DIFN experienced by individual understory white spruce trees, it is possible that the plot readings are not representative of light levels experienced by individual understory white spruce.
- A given stand can experience large differences in light transmittance over a year due to seasonal differences (Lieffers et al. 1999, Constabel and Lieffers 1996). For this project, field sampling occurred from mid-July to early-September. Although it is not expected that plant communities would radically change over this month and a half; it is possible that some minor differences may have occurred.
- Measurements were taken at a height equal to the average mid-crown height of the understory white spruce on the plot. As a result, height where plot understory light data was collected was variable, based on the attributes of the understory white spruce (see Appendix 7.4). This height difference may have impacted the results in undesired ways.

Table 2.2 Description of plot level variables

Variable Name	Description
Plot Size	The size of the plot sampled ($50m^2$ or $100m^2$)
Plot Ecosite	Ecosite assigned based on the *Field Guide to Ecosites of Alberta* Handbooks (Beckingham et al. 1996; Beckingham and Archibald 1996)
Overstory Species and composition (ground call)	Ground call of overstory tree species and composition (E.g. Aw 8 Pb2 – would mean of the Overstory species 80% were Trembling aspen and 20% were Balsam poplar)*.
Overstory Crown Closure – Ground Call (OCC)	Ground call of overstory crown closure percentage (E.g. A call of 80% would mean the overstory vegetation cover 80% of the overhead sky.)
Understory Crown Closure at Stump Height (0.3 m) – ground call (UCC_Stump)	Ground call of percentage of crown closure experienced at stump height (0.3m). All understory competitive vegetation was counted (this measurement excluded overstory trees and understory white spruce).
Understory Crown Closure at Breast Height (1.3 m) – ground call (UCC_Breast)	Ground call of percentage of crown closure experienced at breast height (1.3m). All understory competitive vegetation was counted (this measurement excluded overstory trees and understory white spruce).
Light Transmittance (DIFN)	Measurements of diffuse non-interceptance light transmittance were taken with an LAI 2000 instrument (see Appendix 7.4). Recorded as a proportion of light transmitted.

* - Aw – Trembling Aspen Pb – Balsam poplar

Table 2.3 Description of sampled individual overstory tree variables

Variable Name	Description
Tree Species	Tree species
Height of Tree	Height of overstory tree measured in metres
Height to Live Crown	Height to live crown of overstory tree measured in metres
Diameter Breast Height (DBH)	Trees greater than 1.3m in height, had a measurement of diameter at breast height (in centimeters).
Crown Class	Overstory deciduous trees assigned either: Dominant, Co-Dominant, or Intermediate crown class. Overstory coniferous trees assigned either: Dominant, or Co-Dominant Crown Class.
Breast Height Age	Age at breast height (1.3m) measured in years
Overstory Tree Defect	General description of tree defect into one of the following classifications: No Visible Damage, Minor Visible Damage, Severe Visible Damage, Dead (see appendix 7.9.9 – for more details)

Table 2.4 Description of sampled individual understory tree variables

Variable Name	Description
Regeneration Type	Each understory Sw* was identified as either natural or planted regeneration
Understory Species	Understory Species
Height of Tree	Total height of all understory Sw trees was measured in metres.
Height to Live Crown	Total height to live crown of all understory Sw trees was measured in metres.
Crown Length	Total crown length (m) for each individual understory Sw. Calculated by the formula: Total Height – Height to Live Crown
Diameter Breast Height	Understory Sw greater than 1.3m in height had a breast height diameter measurement taken (cm).
Diameter Root Collar	Understory Sw less than 1.3m in height had a root collar diameter measurement taken (cm).
Crown Class	Understory Sw assigned to either Intermediate or Suppressed Crown Class.
Stump Height Age	Age at stump height (0.3m).
Breast Height Age	Age at breast height (1.3m)
Tree Code – Bole	Description of damage to the bole of understory Sw
Tree Code – Leader	Description of damage to the leader of understory Sw
Tree Code – Canopy	Description of damage to the canopy of understory Sw
Tree Defect / OK	Based on above three tree codes an assessment of total understory tree defect was made.
Three Year Increment	Three-year periodic height increment (cm); measured by the length of the three most recent internodes.

* Sw - White Spruce

Table 2.5 Description of derived plot variables

Variable Name	Description
Total Crown Closure	Percentage crown closure for all understory and overstory competition (understory white spruce excluded). Calculated by adding overstory crown closure to stump height crown closure. The maximum possible value is 200% (i.e. 100% overstory crown closure + 100% understory stump height crown closure).
Overstory Density of Deciduous Trees Per Hectare.	Total overstory deciduous tree density per hectare (dead trees not included).
Overstory Density of Coniferous Trees Per Hectare.	Total overstory coniferous tree density per hectare for each plot (dead trees not included).
Overstory Density of Coniferous + Deciduous Per Hectare	Total overstory tree density per hectare (coniferous + deciduous -dead trees not included).
Overstory Density of Dead Trees Per Hectare.	Dead overstory tree density per hectare.
Overstory Basal Area Per Hectare	Basal area (m^2) per hectare based on overstory trees only.
Coniferous Basal Area Per Hectare	Basal area (m^2) per hectare based on overstory coniferous trees only.
Deciduous Basal Area Per Hectare	Basal area (m^2) per hectare based on overstory deciduous trees only.
Tree Spacing Factor (SF)	Tree spacing factor based on overstory trees only. SF= SQRT(10000/overstory tree density per ha)/average overstory height
Coniferous Tree Spacing Factor (SFCON)	Tree spacing factor based on overstory coniferous trees only. SFCON = SQRT(10000/ overstory coniferous density per ha)/average overstory height
Deciduous Tree Spacing Factor (SFDEC)	Tree spacing factor based on overstory deciduous trees only. SFDEC = SQRT(10000/overstory deciduous density per ha)/average overstory height
Site Index Trembling Aspen*	Site Index for aspen (50 year reference age)
Site Index White Spruce*	Site Index for white spruce (50 year reference age)
Understory Density of Sw Per Hectare.	Total understory Spruce density per hectare (dead trees not included).
Understory Density of Non-Sw Species Per Hectare.	Total understory density per hectare (excluding white spruce and dead trees).
Understory Density Per Hectare (both Sw and Non-Sw species).	Total understory density per hectare for all tree species (dead trees not included).
Understory Dead Per Hectare.	Dead understory tree density per hectare (dead trees not included).

* - All above variables were calculated for each plot except for the Site Index values that were done at the stand level.

Table 2.6 Description of derived individual understory white spruce variables

Variable Name	Description
Relative Crown Length (RCL)	Relative crown length (m) for each individual understory Sw. RCL = Crown Length /Total height
Average Annual Height Increment (AAHI)	Three year increment divided by three to obtain an average annual increment (cm).
Relative Annual Height Increment (RAHI)	Relative annual height increment calculated by the following equation: Average Annual Height Increment /Total tree height
Weighted Annual Height Increment (WAHI)	Weighted relative annual height increment calculated by the following equation: Average Annual Height Increment /SQRT(Total Tree Height). Note: all variables were converted to metres.

2.5 Extraneous variables

When sampling natural stands, it is impossible to control and quantify all site variables. This often results in a high variance. The stand selection rules (described above) were developed to reduce the impact from extraneous variables. However, extraneous variables will still impact the results of this study. Some of the variables not measured but potentially impacting the results are:

- Climate – Long-term climatic factors have a significant impact on forest vegetation (Hogg 1994). In both sampling regions, it is expected that each stand will experience slightly different (but, relatively comparable) climatic factors. In the Lower Foothills sub-region added complexities are caused by differences in aspect and elevation. However, the nature of the sampling protocol (sampling only stands with a deciduous dominated overstory and a viable white spruce understory) should preclude sampling in locations where extremes in climate would adversely impact the growth of understory white spruce.
- Soils – Soil type can significantly impact forest communities. However, the sampling protocol (deciduous dominated overstory with a viable white spruce understory) should preclude sampling in locations where soil properties could adversely impact the growth of understory white spruce. Plot eco-site calls might be useful in identifying these differences as well.
- Stand History and Disturbance Type – The current species composition of a stand is a result of the composition present prior to the last disturbance as well as the type and intensity of the disturbance itself (Greene et al. 1999). No compatible stand history information was available for these sampling regions, therefore stand history information was not considered. As for disturbance type, basic AVI information was available. According to AVI relatively few stands had a recorded disturbance (10 of 53 stands in the

Boreal sub-region, and 3 of 24 stands in the Lower Foothills sub-region). In the few stands that had a disturbance each event occurred at least 9 years ago. Since the study is interested in the growth of understory white spruce within the last 3 years, it is assumed that the impacts of stand origin type and disturbance are minimal.

- Spruce seed source – In natural stands, the regeneration of white spruce is dependent upon a seed source. However, of tree species in Alberta white spruce has one of the highest coefficients of variation for annual seed production (Greene et al. 1999); resulting in unpredictable regeneration. This study reduced the impact of this variable by sampling only those stands that had a significant understory spruce presence and by evaluating stand suitability on measured height growth increments rather than on density levels.

2.6 Data grouping

Due to the wide range of understory white spruce heights, it was impossible to measure the same variables on every tree. For example, trees taller than 1.3m could have a measurement of diameter and age at breast height, while trees less than 1.3m in height obviously could not. This made it necessary to divide the understory data by trees above and below 1.3m, which resulted in two data sets for each eco-region or four separate data sets in total.

1. Boreal sub-region understory white spruce greater than 1.3m in height
2. Boreal sub-region understory white spruce less than 1.3m in height
3. Lower Foothills sub-region understory white spruce greater than 1.3m in height
4. Lower Foothills sub-region understory white spruce less than 1.3m in height

Table 2.7 provides a brief summary of the numbers of plots and trees sampled.

Table 2.7 Summary of frequency of sampling by sub-region

			Living Understory White Spruce Sampled		Living Overstory Trees Sampled		
Sub-region	**Stands Sampled**	**Plots Sampled**	**Less Than 1.3m Tall**	**Greater Than 1.3m Tall**	**Aspen**	**Balsam Poplar**	**White Spruce**
Boreal	53	159	1229	859	1441	239	138
Lower Foothills	23	69	347	308	253	128	26

2.7 Data Analysis

Initially, the four data sets used in this project were analyzed separately with no intent to do any combined analysis (using two or more data sets together). However, similarities in some of the results led to subsequent analysis with some pooling of the data (mainly by sub-region).

The analysis process used was the same for each set of data and for each dependent variable analyzed. The first step was to understand the interaction between understory spruce dependent variables and each potential explanatory variable. First, quantitative explanatory variables were plotted against the dependent variable and the general form (linear, exponential, etc.) of the relationship was evaluated. Next regression models were fit to the data. The variables with the strongest relationships were then used to produce a multiple regression model (all regression analysis were completed by using *The SAS System* computer software developed by the *SAS Institute Inc.*). The final step was to investigate how closely the final model predicts the dependent variable, by comparing predicted to the measured values.

The growth models produced in this study are based on stand conditions at the time of sampling. Normally when modeling future growth increments, predictions should be based on stand conditions at the start of the projection period and not at the end. However, in this study because there was no historical data describing the stand over the prediction period (3 years ago) it was assumed that stand conditions at the end of the projection period resemble the conditions at the start of the period.

3 Results and discussion

The primary focus of the study was to formulate a height increment model for understory white spruce. The bulk of the analysis focused on developing this relationship. During the height increment model building process it was revealed that relative crown length (RCL) would play a major role in the final model. RCL is not a commonly collected field variable; therefore a model was developed for predicting RCL as well.

In addition, regression analysis was also used to conduct a preliminary investigation of understory white spruce mortality. Because of the initial uncertainty about the ability to estimate time since death for dead trees remaining in the stand, this analysis was considered as only a minor component of the study.

3.1 Height increment model formation for understory spruce greater than 1.3m tall

In the Boreal sub-region, a total of 859 understory white spruce greater than 1.3m tall were measured; and of those, 534 had a height increment measurement taken. In the Lower Foothills, a total of 308 understory white spruce greater than 1.3m tall were measured; and of those, 195 had a height increment measurement taken. These data points were the basis for the following analysis.

3.1.1 Average annual height increment and quantitative explanatory variables

A regression analysis of average annual height increment (AAHI) versus each quantitative explanatory variable showed that in some cases a linear form was the best fit; however, more often non-linear forms fit best. For both sampling sub-regions data measured directly from individual understory white spruce (i.e. crown length and age at breast height) tended to fit best with an exponential or power equation; whereas, stand competition variables often had either a quadratic or linear relationship with AAHI. Equation forms and fit statistics are located in Table 3.1 and Table 3.2.

In the Boreal sub-region, the relationship between AAHI and quantitative explanatory variables was generally weak. The best predictive explanatory variable with regard to AAHI was relative crown length (R^2 = 0.4242 in power form). The second strongest relationship was with breast height age (R^2 = 0.3151 in power form), with the third strongest being overstory coniferous

density/ha ($R^2 = 0.3131$ in exponential form). It is interesting to note that while it was anticipated that site index would be an important variable in predicting AAHI, the results did not lead to its inclusion in any models. This finding is described later in Section 3.2.3.

For the Lower Foothills sub-region the relationship between AAHI and the quantitative explanatory variables was weak, especially with regard to competition variables. Only overstory tree spacing factor appeared to have any significant relationship. The variables with the strongest relationship with AAHI were crown length ($R^2 = 0.5589$), relative crown length ($R^2 = 0.3912$) and age at breast height ($R^2 = 0.3223$). The strongest competition variable was overstory tree spacing factor ($R^2 = 0.3248$).

When multi-variable regression was attempted the results were not satisfactory. In the Lower Foothills sub-region, no competition variables could be paired with RCL to significantly (at 95% confidence) improve an AAHI prediction model. Similarly, in the Boreal sub-region, almost all models were not significantly improved by competition variables (at 95% confidence). The two exceptions were when tree spacing factor (SF) and coniferous density were used. However, both of these models were only very slightly influenced by the competition variables (in fact, so weak was the influence that it was essentially a single variable model) and they tended to respond to data in an unexpected manner. This resulted in the need to look for another dependent variable.

Table 3.1 Boreal sub-region - regression models for predicting average annual height increment

Model	Equations and Variables for Predicting Average Annual Height Increment	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Individual Understory White Spruce Characteristics								
1	X = Understory Tree Height $= B0 + B1 \cdot X$ (Linear)	B0 B1	11.7357 0.6327	10.5439 0.3419	12.9274 0.9235	Y Y	0.0332	72.35
2	X = Understory Height to Live Crown $= B0 \cdot X^{B1}$ (Power)	B0 B1	13.5644 -0.2135	12.8363 -0.2738	14.2925 -0.1532	Y Y	0.0811	68.77
3	X = Understory Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	10.8931 0.4742	10.1673 0.4112	11.6189 0.5371	Y Y	0.2906	53.09
4	X = Understory Relative Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	27.2375 1.4255	25.3174 1.2446	29.1575 1.6065	Y Y	0.4242	43.09
5	X = Understory Diameter Breast Ht $= B0 + B1 \cdot X$ (Linear)	B0 B1	11.7235 0.7627	10.7105 0.4934	12.7365 1.0270	Y Y	0.0570	70.57
6	X = Age at Breast Height $= B0 \cdot EXP(B1 \cdot X)$ (Exponential)	B0 B1	15.2815 -0.0319	13.4989 -0.0853	17.0641 0.0216	Y N	0.3151	71.95
Competition Variables								
7	X = Understory Crown Closure at 0.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	7.4536 0.1923 -0.00064	5.6059 0.0888 -0.00183	9.3013 0.2958 0.000557	Y Y N	0.1652	62.59
8	X = Understory Crown Closure at 1.3m $= B0 + B1 \cdot X$ (Linear)	B0 B1	12.1920 0.0880	11.1242 0.0450	13.2598 0.1310	Y Y	0.0295	72.63
9	X = Overstory Coniferous Density / Ha $= B0 \cdot EXP(B1 \cdot X)$ (Exponential)	B0 B1	14.1970 0.00091	13.0679 -0.00304	15.3260 0.00487	Y N	0.3131	71.23
10	X = Overstory Basal Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	18.1983 -0.2115	16.9888 -0.2593	19.4077 -0.1637	Y Y	0.1244	65.53
11	X = Overstory Tree Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	1.1653 83.2073 -92.0397	-2.8384 51.8928 -141.4	5.1690 114.5000 -42.6970	N Y Y	0.1359	69.15

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)

Table 3.2 Lower Foothills sub-region - regression models for predicting average annual height increment

Model	Equations and Variables for Predicting Average Annual Height Increment	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Individual Understory White Spruce Characteristics								
1	X = Understory Tree Height $= B0 + B1 \cdot X$ (Linear)	B0 B1	6.7716 2.4944	4.1963 2.0114	9.3469 2.9773	Y Y	0.3686	108.4
2	X = Understory Height to Live Crown $= B0 \cdot X^{B1}$ (Power)	B0 B1	16.9385 0.1401	14.9448 -0.00177	18.9322 0.2819	Y N	0.0443	164.1
3	X = Understory Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	10.4866 0.6139	9.0614 0.5285	11.9117 0.6992	Y Y	0.5589	75.7
4	X = Understory Relative Crown Length $= B0 \cdot EXP(B1 \cdot X)$ (Exponential)	B0 B1	3.0167 2.7995	1.6833 2.1952	4.3502 3.4038	Y Y	0.3912	104.5
5	X = Understory Diameter Breast Ht $= B0 \cdot X^{B1}$ (Power)	B0 B1	8.5985 0.5588	6.8871 0.4605	10.3098 0.6571	Y Y	0.4701	96.5
6	X = Age at Breast Height $= B0 \cdot X^{B1}$ (Power)	B0 B1	11.2327 0.2353	6.8138 0.1022	15.6515 0.3685	Y Y	0.3223	168.3
Competition Variables								
7	X = Understory Crown Closure at 0.3m $= B0 + B1 \cdot X$ (Linear)	B0 B1	11.1685 0.1456	7.9351 0.0863	14.4018 0.2049	Y Y	0.1084	151.5
8	X = Understory Crown Closure at 1.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	14.5964 0.3632 -0.0032	11.7164 0.0617 -0.00769	17.4764 0.6647 0.00129	Y Y N	0.0477	162.6
9	X = Overstory Coniferous Density / Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	18.1228 -0.00268	16.1674 -0.0096	20.0783 0.00424	Y N	0.0030	169.4
10	X = Overstory Basal Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	21.7612 -0.1117	18.3459 -0.1947	25.1766 -0.0287	Y Y	0.0352	163.9
11	X = Overstory Tree Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	18.9253 -57.35 241.9	1.2936 -263 -314	36.557 148.3 797.8	Y N N	0.3248	140.1

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)

3.1.2 Relative crown length and relative height increment

The results from Table 3.1 and Table 3.2 suggested that live crown length was perhaps the most important variable when attempting to predict future height increment. In the Boreal sub-region, using a relative measure of crown length (relative crown length - RCL) improved this relationship for predicting AAHI from an R^2 of 0.2906 for crown length to an R^2 of 0.4242 for RCL. In the lower foothills, using RCL had a weaker relationship with AAHI (an R^2 of 0.5589 for crown length compared to an R^2 of 0.3912 for relative crown length); however, RCL would prove to be a better variable for predicting height increment.

Using crown length (CL) for predicting AAHI became problematic because it showed a high correlation (0.8657) with total tree height (Figure 3.1). This strong relationship demonstrated that CL is more indicative of total tree height rather than being a sign of tree vigor. Including CL in a model resulted in predictions where taller trees simply grow faster than shorter trees regardless of

site and competition. In comparison, there was relatively weak correlation (-0.2613) between RCL and total height (Figure 3.1). It appears that RCL is a more desirable measure of understory white spruce vigor.

The importance of relative measurements in crown length and the unsatisfactory results for the AAHI models suggested a relative measurement of height increment should be considered as well. During field sampling the size of understory white spruce measured was quite variable with trees from 1.3m in height to just over 15m in height. Due to the high variability of height increments between trees, regression analysis showed only a weak relationship between height and AAHI (Table 3.1). However, when grouped into height classes it was clear that understory white spruce trees above 5m had increased potential for height increments greater than 25cm/year (Table 3.3). Understory spruce between 1.3m and 1.99m tall had only a 2.7% chance of having an AAHI greater than 25cm, compared to over 20% for trees greater than 5 m tall.

As a variety of different sized (and aged) understory white spruce were measured during this study, any predictive height model must rationalize these differences in a reasonable way. For example, it is possible that a small understory spruce tree (from stand A) that is growing very well could have an AAHI that is less than a relatively large understory spruce (from stand B) that is performing below average. Therefore, using AAHI as the dependant variable will result in stand B appearing to be more favorable for spruce growth (when it possibly is not). A relative measure of height increment was used in an attempt to have a standard measure of height growth that was comparable regardless of tree height.

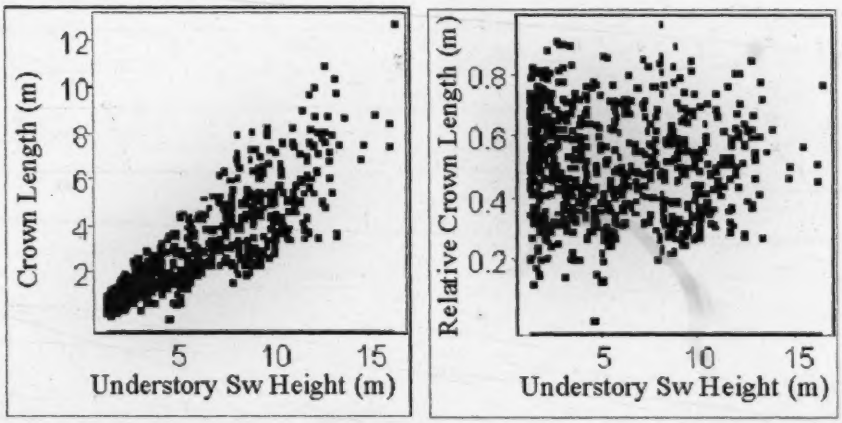

Figure 3.1 Boreal sub-region - comparison of height versus crown length and relative crown length of each individual understory white spruce (Sw)

Table 3.3 Boreal sub-region – frequency of understory white spruce with an average annual height increment (AAHI) greater than 25cm by height class of tree

Height Class Number	Height Class (m)	Number of Observations with a total height measurement and increment measurement	Number of Observations with an AAHI Greater than 25cm	Percentage greater than 25 cm
1	1.3 to 1.99	227	6	2.7%
2	2 to 4.99	227	29	12.8%
3	5 to 9.99	60	15	25%
4	10 to 15.00	20	4	20%

3.1.3 Relative average annual height Increment (RAHI)

Explanatory variables plotted against RAHI showed both linear and non-linear (exponential, quadratic and power) relationships (Table 3.4). In general, data sampled from the individual understory trees tended to show primarily an exponential or power form and secondarily a linear form. Stand competition variables usually had either a quadratic or linear relationship with RAHI.

Using RAHI as the dependent variable resulted in a marked improvement of relationship with the explanatory variables over that observed for AAHI. For example, breast height age showed the strongest predictive ability for RAHI as it improved greatly from R^2 of 0.3151 for AAHI to an R^2 of 0.7314 R^2 for RAHI. The relationship with overstory basal area also improved significantly from an R^2 of 0.1244 for AAHI to an R^2 of 0.3591 for RAHI. Therefore, using RAHI appeared to improve the predictive ability of most explanatory variables. However, problems with use of RAHI arose.

Table 3.4 Boreal sub-region - regression models for predicting relative annual height increment by individual explanatory factors based on data collected in the Boreal sub-region

Model	Equations and Variables for Predicting Relative Annual Height Increment	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Individual Understory White Spruce Characteristics								
1	X = Understory Tree Height $= B0 \cdot EXP(B1 \cdot X)$ (Exponential)	B0 B1	0.1032 -0.2282	0.0906 -0.2807	0.1158 -0.1758	Y Y	0.2437	0.00103
2	X = Understory Height to Live Crown $= B0 \cdot EXP(B1 \cdot X)$ (Exponential)	B0 B1	0.1233 -0.8210	0.1164 -0.9039	0.1302 -0.7380	Y Y	0.6312	0.00050
3	X = Understory Crown Length $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0635 -0.0044	0.0583 -0.00665	0.0686 -0.00224	Y Y	0.0287	0.00132
4	X = Understory Relative Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.1285 1.8283	0.1203 1.6460	0.1366 2.0106	Y Y	0.5805	0.00057
5	X = Understory Diameter Breast Height $= B0 \cdot EXP(B1 \cdot X)$ (Exponential)	B0 B1	0.0808 -0.1703	0.0743 -0.2108	0.0872 -0.1298	Y Y	0.2035	0.00108
6	X = Age at Breast Height $= B0 \cdot EXP(B1 \cdot X)$ (Exponential)	B0 B1	0.1051 -0.0781	0.0994 -0.0885	0.1107 -0.0677	Y Y	0.7314	0.00051
Competition Variables								
7	X = Overstory Crown Closure $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0825 -0.00073	0.0776 -0.00083	0.0874 -0.00062	Y Y	0.2483	0.00102
8	X = Understory Crown Closure at 0.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0113 0.00179 -0.00001	0.00404 0.00138 -0.00002	0.0186 0.00219 -0.0000078	Y Y Y	0.2904	0.00097
9	X = Understory Crown Closure at 1.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0329 0.00245 -0.00004	0.0271 0.00192 -0.00005	0.0387 0.00299 -0.00003	Y Y Y	0.1334	0.00118
10	X = Overstory Coniferous Density / Ha $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0687 -0.00008 3.11E-11	0.0650 -0.00009 2.363E-8	0.0723 -0.00006 3.856E-8	Y Y Y	0.1967	0.00109
11	X = Overstory Basal Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0871 -0.00153	0.0827 -0.00171	0.0915 -0.00136	Y Y	0.3591	0.00087
12	X = Understory Sw Density/ha $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0246 0.00000842 -2.13E-10	0.0200 0.00000711 -2.74E-10	0.0291 0.00000974 -1.51E-12	Y Y Y	0.3847	0.00083
13	X = Overstory Tree Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	-0.0332 0.5734 -0.6127	-0.0452 0.4867 -0.7299	-0.0212 0.6602 -0.4955	Y Y Y	0.4010	0.00086

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)

3.1.4 Problems with using relative annual height increment (RAHI) and the introduction of weighted annual height increment

RAHI resulted in improved correlation with the majority of explanatory variables when compared to AAHI. However, after further analysis, problems with using RAHI emerged. Average potential height increment of understory spruce did not increase proportionally with height. Dividing AAHI by total height caused taller trees to predominantly have a lower RAHI than shorter trees.

To summarize, RAHI was introduced because height growth potential increases with total tree height. Therefore, AAHI was plagued with a problem where if the AAHI measurements were

equal for two trees of significantly different heights, they would (incorrectly) be assumed to be growing with the same vigor. However, when RAHI was used the opposite situation occurred. For example, a 10m tall understory spruce with a 40cm AAHI (a good growth rate, Figure 3.2) will have a RAHI value of only 0.04 (which was below the mean for the population). Obviously this was not a fair representation of how well the tree was growing. Therefore, when comparisons were made between understory trees of different age and heights, both RAHI and AAHI were not satisfactory dependant variables.

An alternative height increment variable was needed. The problem with RAHI arose because potential average height increment did not increase linearly with height. Therefore, in any ratio between height increment and total height, it was important that height increment be given more weight than total tree height. A solution was the development of a variable called weighted annual height increment (WAHI), calculated by the equation:

$$\text{WAHI} = \frac{AAHI(m)}{\sqrt{Total\ Height(m)}}$$

WAHI resulted in more realistic relationships between different height classes. A 10 metre tall tree with a growth increment of 40cm had a WAHI of 0.127, which was well above the average for the population (Figure 3.2). Therefore, it was decided that WAHI was a more useful explanatory than RAHI and AAHI.

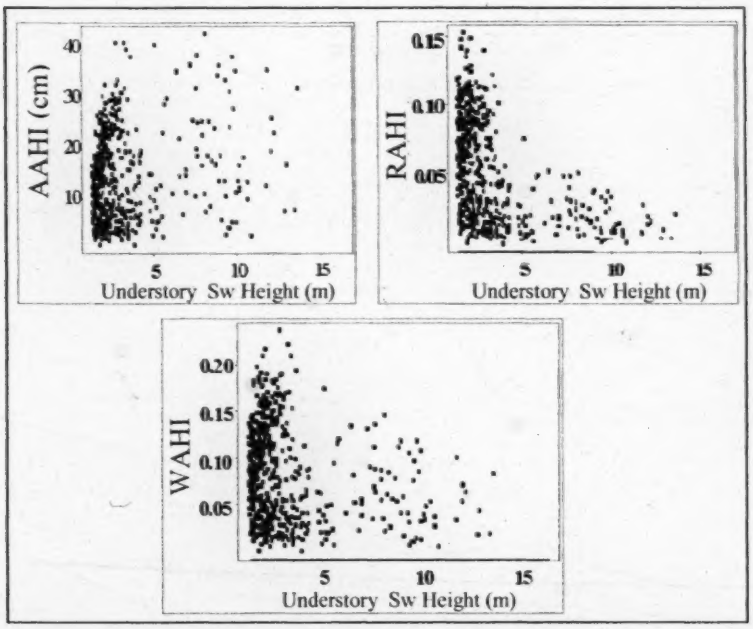

Figure 3.2 Plots of average annual height increment (AAHI), relative average height increment (RAHI), and weighted average height increment (WAHI) versus understory white spruce (Sw) height

3.1.5 Weighted average annual height increment (WAHI)

Explanatory variables measured directly from individual understory white spruce tended to have either a power or exponential relationship with WAHI, whereas, competition variables tended to have a quadratic or linear relationship with WAHI. These trends were essentially the same as the results for AAHI and RAHI.

In the Boreal sub-region, WAHI showed the strongest relationship with RCL with an R^2 of 0.6089 (Table 3.5). The second strongest relationship was between WAHI and breast height age (R^2=0.5437), while the strongest competition variable was tree spacing factor (R^2=0.3376). Similar results occurred in the Lower Foothills sub-region with RCL showing the strongest relationship with WAHI (R^2=0.4808) (Table 3.6) and breast height age was the third strongest (R^2=0.3052). Overstory tree spacing factor was the strongest competition variable (R^2=0.3462) however, the coefficient values were not significant at 95% confidence.

Interestingly, both data sets arrived at the same general conclusion. RCL was the most important variable for estimating height increment, followed by age at breast height. In addition, both overstory spacing factor and understory crown closure at stump height (0.3m) were strong competitive variables.

Table 3.5 Boreal sub-region - regression models for predicting weighted annual height increment by individual explanatory factors

Model	Equations and Variables for Predicting Weighted Annual Height Increment	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Individual Understory White Spruce Characteristics								
1	X = Understory Tree Height $= B0 \cdot EXP(B1 \cdot X)$ (Exponential)	B0 B1	0.1045 -0.0693	0.0951 -0.0979	0.1140 -0.0407	Y Y	0.0563	0.00246
2	X = Understory Height to Live Crown $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.0796 -0.4248	0.0758 -0.4745	0.0833 -0.3750	Y Y	0.3920	0.00159
3	X = Understory Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.0781 0.1771	0.0729 0.0981	0.0833 0.2561	Y Y	0.0433	0.00250
4	X = Understory Relative Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.1863 1.6973	0.1759 1.5426	0.1957 1.8520	Y Y	0.6089	0.00102
5	X = Understory Diameter Breast Height $= B0 \cdot EXP(B1 \cdot X)$ (Exponential)	B0 B1	0.0956 -0.0483	0.0887 -0.0725	0.1026 -0.0241	Y Y	0.0352	0.00252
6	X = Age at Breast Height $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.1408 -0.2637	0.1301 -0.3090	0.1516 -0.2184	Y Y	0.5437	0.00167
Competition Variables								
7	X = Understory Crown Closure at 0.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0280 0.00214 -0.00001	0.0178 0.00157 -0.00002	0.0381 0.00271 -0.0000067	Y Y Y	0.2782	0.00189
8	X = Understory Crown Closure at 1.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0555 0.00305 -0.00004	0.0473 0.00229 -0.00006	0.0636 0.00380 -0.00003	Y Y Y	0.1118	0.00232
9	X = Overstory Coniferous Density / Ha $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.1022 -0.00010 3.909E-8	0.0970 -0.00012 2.86E-8	0.1073 -0.00008 4.957E-8	Y Y Y	0.1751	0.00216
10	X = Overstory Basal Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.1248 -0.00193	0.1184 -0.00219	0.1312 -0.00168	Y Y	0.2977	0.00183
11	X = Understory Sw Density/ha $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0491 0.00000967 -2.39E-10	0.0423 0.00000769 -3.33E-10	0.0559 0.000012 -1.46E-10	Y Y Y	0.2713	0.00191
12	X = Overstory Tree Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	-0.0281 0.7332 -0.7873	-0.0456 0.6067 -0.9581	-0.0106 0.8597 -0.6164	Y Y Y	0.3376	0.00182

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)

Table 3.6 Lower Foothills sub-region - regression models for predicting weighted annual height increment by individual explanatory factors

Model	Equations and Variables for Predicting Weighted Annual Height Increment	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Individual Understory White Spruce Characteristics								
1	X = Understory Tree Height $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.0705 0.1565	0.0571 0.0334	0.0839 0.2797	Y Y	0.0321	0.00249
2	X = Understory Height to Live Crown $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.0904 -0.2397	0.0833 -0.3498	0.0975 -0.1296	Y Y	0.0846	0.00236
3	X = Understory Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.0702 0.278	0.0618 0.1857	0.0787 0.3702	Y Y	0.1780	0.00212
4	X = Understory Relative Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.1834 1.5122	0.1618 1.223	0.2051 1.8015	Y Y	0.4808	0.00134
5	X = Understory Diameter Breast Height $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.0696 0.1849	0.0584 0.0883	0.0808 0.2815	Y Y	0.1200	0.00243
6	X = Age at Breast Height $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.1182 -0.0873	0.0921 -0.1752	0.1444 0.000481	Y N	0.3052	0.00263
Competition Variables								
7	X = Overstory Crown Closure $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.1321 -0.00093	0.1146 -0.00127	0.1497 -0.00060	Y Y	0.1398	0.00222
8	X = Understory Crown Closure at 0.3m $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0472 0.00086	0.0355 0.000645	0.0588 0.00108	Y Y	0.2461	0.00194
9	X = Understory Crown Closure at 1.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0676 0.00189 -0.00001	0.0569 0.000763 -0.00003	0.0784 0.00301 4.52E-06	Y Y N	0.1278	0.00226
10	X = Overstory Coniferous Density / Ha $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0879 -0.00002 6.37E-09	0.0798 -0.0001 -5.71E-08	0.0959 0.00006 6.99E-08	Y N N	0.0053	0.00258
11	X = Overstory Basal Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.1004 -0.0004	0.0868 -0.00073	0.114 -0.00007	Y Y	0.0293	0.0025
12	X = Understory Sw Density/ha $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.4244 -0.2099	0.1584 -0.2947	0.6905 -0.1251	Y Y	0.0997	0.00232
13	X = Overstory Tree Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.1313 -0.6948 2.094	0.0641 -1.4786 -0.0252	0.1985 0.0891 4.2132	Y N N	0.3462	0.00204
14	X = Overstory Coniferous Tree Spacing Factor $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0446 0.0471	0.019 0.0193	0.0702 0.0749	Y Y	0.0554	0.00243
15	X = Overstory Deciduous Tree Spacing Factor $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0713 0.0495	0.0619 0.0277	0.0808 0.0712	Y Y	0.0955	0.00233

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)

3.1.6 Boreal sub-region final model selection

In the Boreal sub-region, the variables selected for further analysis were relative crown length (RCL), breast height Age (BAGE), overstory tree spacing factor (SF), understory crown closure at stump height (UCCS), overstory basal area (BA), and understory white spruce density (USWD) (all had an R^2 value with WAHI of greater than 0.25 - Table 3.5). In the Lower Foothills sub-region, the relationships tended not to be as strong, resulting in only four variables of interest for further analysis: RCL, BAGE, SF, and UCCS. Ideally, the final model should have

at least one competition variable, as the objective of the study was to understand competitive factors impacting understory white spruce growth.

In the Boreal sub-region, RCL was chosen as the starting variable in building a multi-variable model because it had the strongest relationship with WAHI (R^2=0.6089) (Table 3.5). Next, a suite of two-variable models was produced where RCL was modeled along with another explanatory factor. All variables (except UCCS – Model 3) significantly improved the prediction of WAHI (Table 3.7), with BAGE giving the greatest improvement by increasing the R^2 to 0.7959. Therefore, it was decided that BAGE would be added to the model as the second variable. The next step was to add one of the remaining competition variables to the model. Model 6 with RCL, BAGE, and SF was selected as the "best" predictive model for WAHI in the Boreal sub-region as each individual variable significantly contributed to the model and with a high R^2 of 0.8116 the model was considered satisfactory to incorporate into the Mixedwood Growth Model (MGM).

To ensure Model 6 was reasonable, the relationship of each individual variable in the final model to WAHI was examined closely. Upon plotting RCL against WAHI, both linear and power forms appeared to fit the RCL - WAHI relationship reasonably well (Figure 3.3). However, the power equation was chosen for two reasons. First, it visually fits the data better and secondly, the linear equation dropped into negative WAHI when RCL was below 0.20, resulting in unrealistic predictions. The power form slowly declined toward zero, which was a more reasonable result (R^2=0.6089).

The use of RCL as a predictor of potential future growth was understandable because the amount of photosynthesizing matter on a plant will improve the potential growth of the plant. Studies are consistent with this general notion that increased live crown results in increased growth potential. For instance, increased needle biomass results in increased seedling growth for engelmann spruce (*Picea engelmannii* Parry ex Engelm.) (Comeau et al. 1993) and exposed crown surface area has been shown to reasonably account for growth in pine stands (Hatch et al. 1975).

The relationship between WAHI and BAGE was best represented by either the power or exponential form (Figure 3.3). The power form was ultimately selected because it was clearly a better predictive tool at breast height ages greater than 35 years, whereas the exponential form significantly under-predicted the growth of these older understory white spruce. However, both

models suggested that the ability of white spruce to put on height increment (WAHI) will decrease the longer it remains in the understory. While the author is not aware of a study that reports on the direct relationship between potential height growth and age of understory white spruce; it has been shown that the ability of understory white spruce to gain significant height-growth-release following thinning diminishes significantly by 45 years (Yang 1991). Assuming this was associated with an overall drop in height growth potential, the premise used in the model (increased age = decreased growth potential) was reasonable.

The relationship between WAHI and Tree Spacing Factor (SF) is somewhat complex. SF is a measure of overstory "crowdedness", considering both stand density and stand average height. SF (Wilson 1951) was calculated by:

$$SF = \frac{\sqrt{10{,}000 / Overstory\ \ Density}}{Average\ Stnd\ Height}$$

The lower SF is, the more crowded the overstory is.

The plot of SF versus WAHI suggested a quadratic form (Figure 3.4) (R^2=0.3376). While the quadratic equation may at first appear confusing, it is consistent with what would be expected. Obviously, an "over-crowded" overstory is detrimental to understory spruce height growth (Groot 1999). Therefore, as a stand becomes less crowded (SF increases) WAHI increases; however, when SF is greater than 0.5 WAHI starts to drop off. A potential reason for this is increased competition from shrubs and herbs in stands with decreased overstory competition. In this study, stands with an SF of 0.5 or less averaged a crown closure at stump height of 42%, this increased to just over 60% when SF was greater than 0.5. These results are consistent with studies done in shelterwoods which show greater height growth of understory white spruce in medium-sized canopy openings, than in large openings or in clear-cuts (Groot 1999). Additionally, overstory cover can reduce the abundance of grass species (especially *Calamagrostis Canadensis* (Michx.)), which can impact the growth of white spruce through both direct competition and by significantly impeding the thawing of soils (Hogg and Lieffers, 1991).

One other point of note is the decrease in WAHI above 0.5 SF appears to be gradual. However, it is a significant decline, because stands with an SF value greater than 0.4 are typically young open stands (Figure 3.4). When compared to the trend of younger understory spruce generally having

a higher WAHI (Figure 3.3), this drop in WAHI is larger then Figure 3.4 suggests, because it is going against the established breast height age relationship.

Table 3.7 Boreal sub-region - summary of multiple regression models predicting weighted annual height increment

Model	Equation for Predicting Weighted Annual Height Increment	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Two-Variable Models								
1	$=B0 \cdot RCL^{B1} \cdot BAge^{B2}$	B0	0.2001	0.1877	0.2125	Y	0.7959	0.00075
		B1	1.5672	1.3975	1.7368	Y		
		B2	-0.0786	-0.1111	-0.0461	Y		
2	$=B0 \cdot RCL^{B1} + B2 \cdot SF + B3 \cdot SF^2$	B0	0.1779	0.1604	0.1953	Y	0.6401	0.00097
		B1	2.4532	2.0121	2.8944	Y		
		B2	0.1942	0.1271	0.2614	Y		
		B3	-0.2733	-0.367	-0.1797	Y		
3	$=B0 \cdot RCL^{B1} + B2 \cdot UCCS + B3 \cdot UCCS^2$	B0	0.1621	0.1487	0.1755	Y	0.6400	0.00094
		B1	1.9093	1.6478	2.1707	Y		
		B2	0.00045	0.00003	0.00088	Y		
		B3	-6.5E-07	-5.4E-06	4.2E-06	N		
4	$=B0 \cdot RCL^{B1} + B2 \cdot USWD + B3 \cdot USWD^2$	B0	0.1638	0.1507	0.1768	Y	0.6319	0.00096
		B1	1.7772	1.5837	1.9708	Y		
		B2	3.74E-06	2.25E-06	5.22E-06	Y		
		B3	-1.1E-10	-1.8E-10	-4.6E-11	Y		
5	$=B0 \cdot RCL^{B1} + B2 \cdot BA$	B0	0.1774	0.1681	0.1866	Y	0.6206	0.00099
		B1	1.3047	1.1047	1.5048	Y		
		B2	-0.00048	-0.00071	-0.00025	Y		
Three-Variable Models								
6	$=B0 \cdot RCL^{B1} \cdot BAge^{B2} + B3 \cdot SF + B4 \cdot SF^2$	B0	0.2121	0.1908	0.2334	Y	0.8116	0.00072
		B1	1.9417	1.6019	2.2814	Y		
		B2	-0.0915	-0.1274	-0.0556	Y		
		B3	0.0948	0.0142	0.1754	Y		
		B4	-0.1669	-0.2726	-0.0611	Y		
7	$=B0 + B1 \cdot RCL + B2 \cdot BAge + B3 \cdot SF + B4 \cdot SF^2$	B0	-0.0615	-0.0784	-0.0446	Y	0.7984	0.00077
		B1	0.1995	0.178	0.2209	Y		
		B2	-0.00027	-0.00049	-0.00004	Y		
		B3	0.2071	0.1063	0.3079	Y		
		B4	-0.2717	-0.4004	-0.143	Y		
8	$=B0 \cdot RCL^{B1} \cdot BAge^{B2} + B3 \cdot USWD + B4 \cdot USWD^2$	B0	0.1949	0.1765	0.2134	Y	0.7967	0.00075
		B1	1.5553	1.3696	1.741	Y		
		B2	-0.0721	-0.1095	-0.0347	Y		
		B3	1.3E-08	-1.7E-06	1.8E-06	N		
		B4	1.6E-11	-5.4E-11	8.7E-11	N		
9	$=B0 \cdot RCL^{B1} \cdot BAge^{B2} + B3 \cdot BA$	B0	0.1974	0.1825	0.2123	Y	0.7961	0.00075
		B1	1.5099	1.2578	1.762	Y		
		B2	-0.0734	-0.1097	-0.0372	Y		
		B3	-0.00007	-0.00032	0.00017	N		

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)
Note: RCL – Relative Crown Length, BAge-Breast Height Age, BA-Basal Area, SF-Overstory Tree Spacing Factor, USWD – Understory White Spruce Density, UCCS – Understory Crown Closure at Stump Height
Double Line = Chosen Model

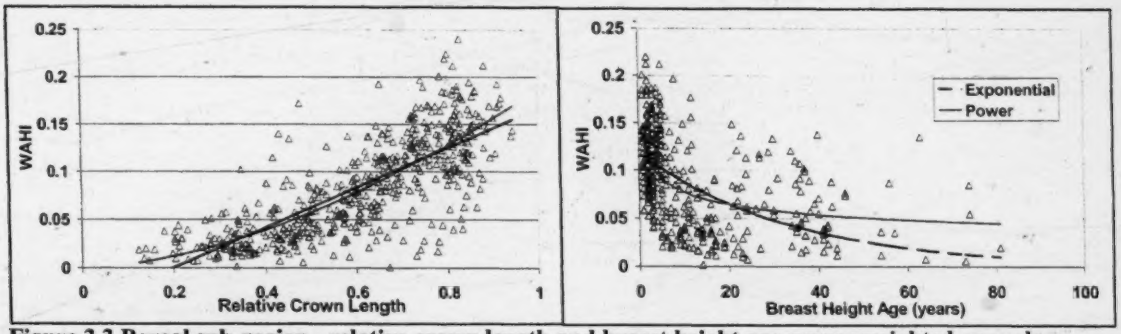

Figure 3.3 Boreal sub-region - relative crown length and breast height age versus weighted annual height increment (WAHI)

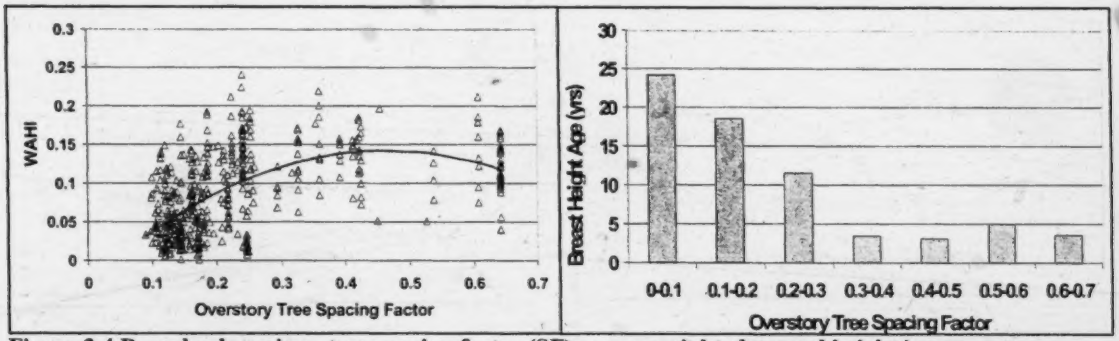

Figure 3.4 Boreal sub-region - tree spacing factor (SF) versus weighted annual height increment (WAHI) and breast height age

Satisfied with the relationship between each individual explanatory variables (RCL, BAGE, and SF) and WAHI, the overall model needed to be assessed. The final selected equation including coefficients was:

$$\text{Predicted WAHI} = 0.2121 \cdot RCL^{1.9417} \cdot BAge^{-0.0915} + 0.0948 \cdot SF - 0.1669 \cdot SF^2 \qquad (1)$$

where

RCL = relative crown length

BAge = breast height age

SF = overstory tree spacing factor

A plot of model predicted WAHI versus observed WAHI showed a distinctly linear relationship. As well, the residual plot showed a relatively uniform distribution of variance (Figure 3.5). Variance increased gradually as the predicted WAHI increased; this was somewhat expected as increased WAHI naturally has an increased chance of variability.

Equation 1 appeared to give satisfactory results for predicting WAHI. However, the model should be applied with the following restrictions:

- Understory white spruce are between 1.3m and 15m tall
- A maximum overstory SF of 0.65.
- A maximum BAGE of 80 years

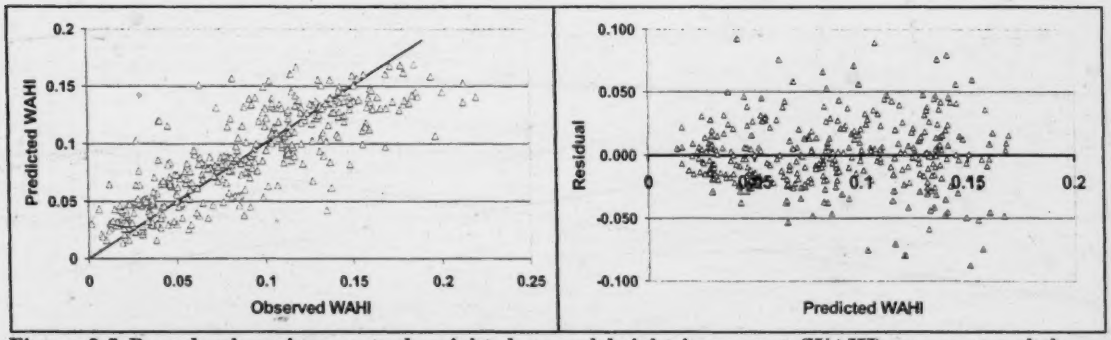

Figure 3.5 Boreal sub-region - actual weighted annual height increment (WAHI) versus sampled WAHI and residual plots of predicted WAHI

3.1.7 Lower Foothills sub-region multiple regression models

In the Lower Foothills sub-region, RCL showed the strongest relationship with WAHI (R^2=0.4808); therefore it was chosen as starting variable for building multiple variable models. BAGE improved the model significantly (R^2=0.5975) when added as the second variable (Table 3.8 – Model 1). Unfortunately, no competition variable added to RCL and BAGE improved the model (Table 3.8) while maintaining all variables as significant (at 95% confidence).

Without a competition variable the model was of limited use, therefore it was decided that breast height age should be dropped as an explanatory variable. An analysis of RCL with competition variables resulted in two two-variable models (Models 3 and 6) giving significant results: RCL with SF and RCL with crown closure at stump height (Table 3.8). The competition variable with the highest R^2 value when plotted against WAHI was SF (Table 3.6). However, the model coefficients were not significant at a 95% confidence interval, making SF of limited use when predicting WAHI (Model 2 - Table 3.8).

In an attempt to select the "best" model, the relationship between WAHI and each potential explanatory variable (from Models 1, 3, and 6) was examined. In the Lower Foothills sub-region, the relationship to WAHI for both RCL and BAGE was consistent with the observations from the Boreal sub-region, demonstrating improved height growth with increased RCL and decreased

growth with increased BAGE (Figure 3.6). This suggested that Model 1 was reasonable; however it was a weak model at best (due to absence of competition variables).

Model 6 included the competition variable coniferous spacing factor (SFCON) as an explanatory variable. Increasing SFCON resulted in increased WAHI (Figure 3.7), which suggested that coniferous trees in the overstory had a negative impact on understory spruce growth. This is consistent with studies that have shown significantly less light is transmitted through overstory coniferous trees compared to deciduous trees (Lieffers and Stadt 1994). Also, overstory white spruce trees directly compete for critical resources, therefore increasing the negative impact on understory white spruce.

Although this relationship between SFCON and WAHI was somewhat expected, the trend was weak with an R^2 of 0.055. This was likely caused by the high variability of the numerous points assigned a SFCON value of 1.0 (all stands with no overstory coniferous trees were assigned an SFCON value of 1.0 – indicating a sparse density of overstory coniferous trees present).

SFCON appeared to impact height growth potential, as all of the 25 WAHI readings greater than 0.15 were from stands with a SFCON greater than 0.8. Additionally, 59 of the 65 understory white spruce that had a WAHI greater than 0.10 were in stands with a SFCON greater than 0.8. This suggested that to achieve maximum possible height increment for understory spruce there must be a limited number of coniferous trees in the overstory. When SFCON is greater than 0.8, the large variance in WAHI may be caused by competition from understory species (Figure 3.7). While SFCON did appear to impact understory white spruce growth, its modest correlation makes it difficult to confidently use SFCON for predicting WAHI.

Model 3 (Table 3.8) used RCL and UCCS to predict WAHI. UCCS had a positive relationship with WAHI (Figure 3.8), suggesting increased understory competition resulted in increased WAHI. One potential reason for this counter-intuitive result was that a high UCCS was indicative of a low overstory crown closure (OCC) (Figure 3.8). Therefore, the improved WAHI linked to increased UCCS was due to decreased competition from overstory trees species, rather than some type of "benefit" from growth in association with understory competition (despite this relationship OCC was not significant at 95% confidence, Model 7-Table 3.8). This means the use of UCCS for predicting WAHI was problematic for two reasons; firstly, this model suggested increased understory competition facilitated increased height growth. Secondly, UCCS is not

commonly collected with field sampling. Therefore, it would be difficult to apply to other situations.

Table 3.8 Lower Foothills sub-region - summary of multiple regression models predicting weighted annual height increment

Model	Equation for Predicting Weighted Annual Height Increment	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Two-Variable Models								
1	$=B0 \cdot RCL^{B1} \cdot BAge^{B2}$	B0	0.2159	0.1735	0.2583	Y	0.5975	0.00154
		B1	1.4340	1.0519	1.8161	Y		
		B2	-0.0740	-0.1368	-0.0112	Y		
2	$=B0 \cdot RCL^{B1} + B2 \cdot SF + B3 \cdot SF^2$	B0	0.1590	0.1298	0.1882	Y	0.6103	0.00122
		B1	1.1879	0.5707	1.8051	Y		
		B2	-0.0416	-0.4414	0.3582	N		
		B3	0.0999	-1.0478	1.2475	N		
3	$=B0 \cdot RCL^{B1} + B2 \cdot UCCS$	B0	0.1579	0.1295	0.1864	Y	0.5005	0.00129
		B1	1.5474	1.2079	1.8869	Y		
		B2	0.00029	0.000081	0.000498	Y		
4	$=B0 \cdot RCL^{B1} \cdot USWD^{B2}$	B0	0.2563	0.1493	0.3634	Y	0.4883	0.00133
		B1	1.4339	1.1341	1.7338	Y		
		B2	-0.0488	-0.1081	0.0105	N		
5	$=B0 \cdot RCL^{B1} + B2 \cdot BA$	B0	0.1834	0.1617	0.2050	Y	0.4808	0.00134
		B1	1.5066	1.1377	1.8754	Y		
		B2	-5.52E-06	-0.00025	0.000234	N		
6	$=B0 \cdot RCL^{B1} + B2 \cdot SFCON$	B0	0.1711	0.1443	0.1980	Y	0.5004	0.00129
		B1	1.9721	1.3958	2.5484	Y		
		B2	0.0232	0.00694	0.0394	Y		
7	$=B0 \cdot RCL^{B1} + B2 \cdot OCC$	B0	0.1823	0.1610	0.2036	Y	0.4811	0.00134
		B1	1.4327	0.9575	1.9079	Y		
		B2	-0.00005	-0.00033	0.000225	N		
Three-Variable Models								
8	$=B0 \cdot RCL^{B1} \cdot BAge^{B2} + B3 \cdot SF + B4 \cdot SF^2$	B0	0.1696	0.1152	0.2239	Y	0.6994	0.00142
		B1	1.0077	0.3068	1.7086	Y		
		B2	-0.0131	-0.0881	0.0620	N		
		B3	-0.0979	-0.7032	0.5074	N		
		B4	0.1326	-1.5401	1.8052	N		
9	$=B0 \cdot RCL^{B1} \cdot BAge^{B2} + B3 \cdot UCCS$	B0	0.1931	0.1384	0.2478	Y	0.6029	0.00153
		B1	1.4854	1.0459	1.9249	Y		
		B2	-0.0644	-0.1366	0.00778	N		
		B3	0.000199	-0.00010	0.000499	N		
10	$=B0 \cdot RCL^{B1} \cdot BAge^{B2} + B3 \cdot SFCON$	B0	0.2085	0.1585	0.2584	Y	0.6055	0.00152
		B1	1.7712	1.0837	2.4588	Y		
		B2	-0.0897	-0.1655	-0.0138	Y		
		B3	0.0198	-0.00359	0.0433	N		
11	$=B0 \cdot RCL^{B1} \cdot USWD^{B2} + B3 \cdot SFCON$	B0	0.2737	0.1322	0.4152	Y	0.5102	0.00128
		B1	1.8672	1.2985	2.4358	Y		
		B2	-0.0701	-0.1459	0.00585	N		
		B3	0.0243	0.00817	0.0403	Y		

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)
Note: RCL – Relative Crown Length, BAge-Breast Height Age, BA-Basal Area, SF-Overstory Tree Spacing Factor, SFCON – Overstory Coniferous Tree Spacing Factor, USWD – Understory White Spruce Density, UCCS – Understory Crown Closure at Stump Height, OCC – Overstory Crown Closure

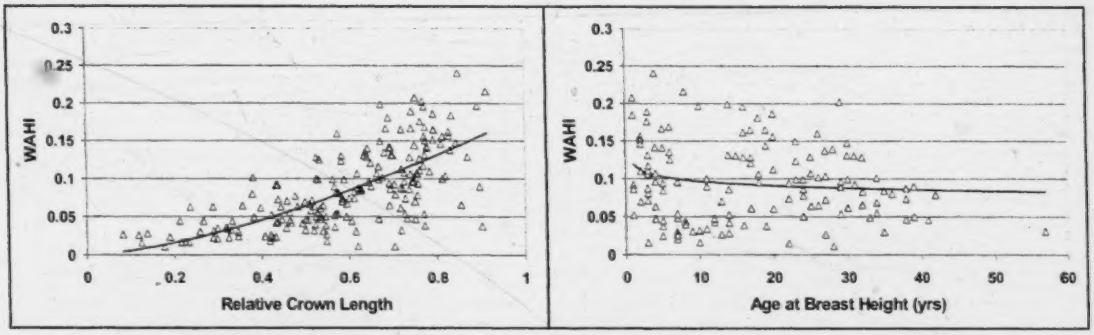

Figure 3.6 Lower Foothills sub-region - relative crown length and breast height age versus weighted annual height increment (WAHI)

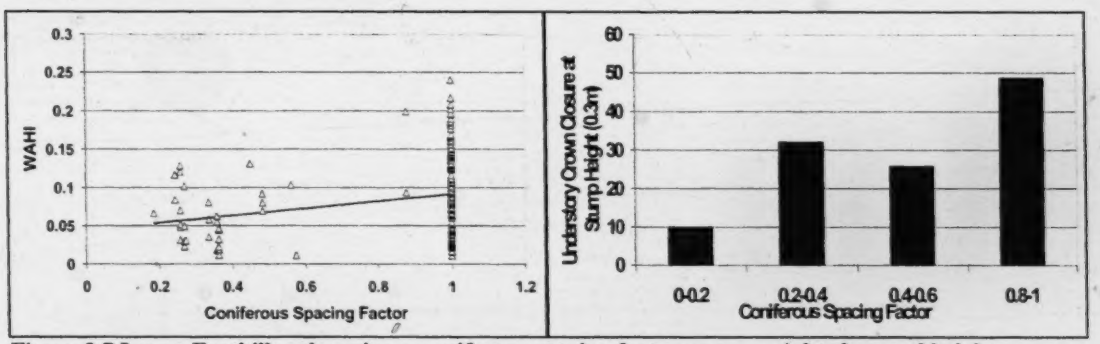

Figure 3.7 Lower Foothills sub-region - coniferous spacing factor versus weighted annual height increment (WAHI) and coniferous spacing factor versus average understory crown closure at stump height (0.3m)

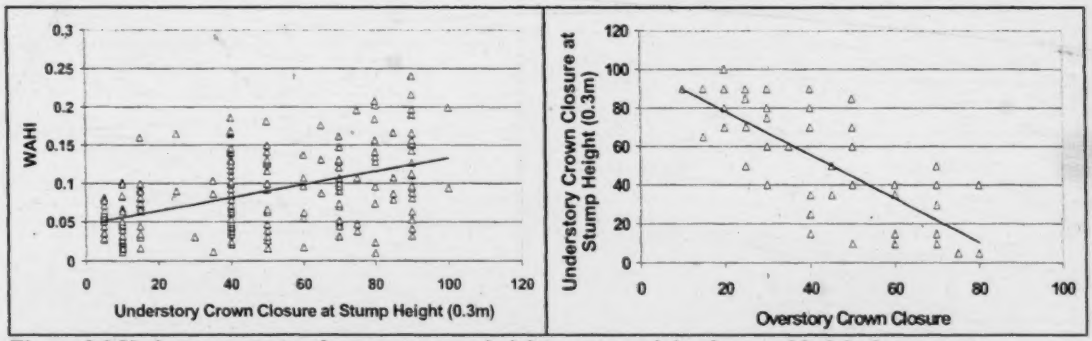
WAHI
Understory Crown Closure at Stump Height (0.3m)
Understory Crown Closure at Stump Height (0.3m)
Overstory Crown Closure

Figure 3.8 Understory crown closure at stump height versus weighted annual height increment (WAHI) and overstory crown closure versus understory crown closure at stump height (0.3m)

Of the three possible models for predicting WAHI in the Lower Foothills sub-region, only the RCL, BAGE model could be used.

$$\text{Predicted WAHI} = 0.2159 \cdot RCL^{1.434} \cdot BAge^{-0.074} \qquad (2)$$

When actual WAHI and predicted WAHI were compared, the results were satisfactory. There was not significant bias present in the model, however the variance was larger than desired (Figure 3.9). This suggested that the model was of limited use. Equation 2 should be applied to the following data only:

- Understory white spruce greater than 1.3m tall
- Breast height age should be a maximum of 45 years

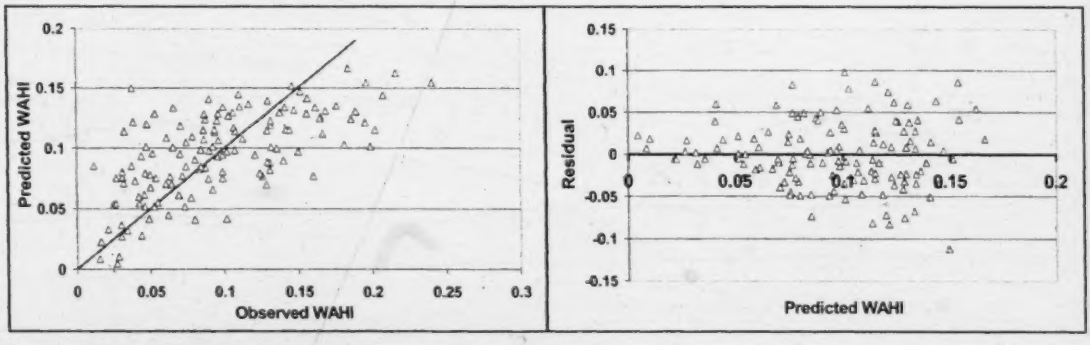

Figure 3.9 Lower Foothills sub-region - actual weighted annual height increment (WAHI) versus predicted WAHI and residual plots of predicted WAHI

3.1.8 Combined final predictive model

It is acknowledged that the factors influencing white spruce height growth will likely be different (in type and severity) between the Lower Foothills and the Boreal sub-regions. However, the similarity of the WAHI models (both using RCL and BAGE, and SF as the strongest competition variable) made it possible to model understory white spruce growth from a combined data set.

The equation form used for the Boreal sub-region data (Equation 1) was also used as the basis for fitting the combined data. The equation after fitting the combined model is as follows (see Table 3.9 for the coefficients 95% confidence interval):

$$\text{Predicted WAHI} = 0.2043 \cdot RCL^{1.7590} \cdot BAge^{-0.0758} + 0.0723 \cdot SF + -0.1355 \cdot SF^2 \qquad (3)$$

Table 3.9 Coefficient values for combined model

Coefficient	Coefficient Estimate	95% Confidence Interval of the Mean	
		Lower Limit	Upper Limit
B0	0.2043	0.1840	0.2245
B1	1.7590	1.4637	2.0544
B2	-0.0758	-0.1069	-0.0446
B3	0.0723	-0.00725	0.1518
B4	-0.1355	-0.2432	-0.0279

The combined model had a reasonably strong relationship to WAHI (R^2=0.7753), and all coefficients except the first (linear) term for SF (B3 -Table 3.9) were significant. When compared to the separate Boreal sub-region model the combined model was not as good a model as indicated by the slightly lower R^2 value (0.7753 for combined model versus 0.8116 for boreal sub-region model) and higher residual mean square (0.00090 for combined model versus 0.00072 for the boreal sub-region model). However, the combined model was a significant improvement over the Lower Foothills sub-region model because it had a higher R^2 value (0.7753 versus 0.5975) and a competition variable was included. Figure 3.10 shows that the Lower Foothills sub-region data points were relatively equally spread throughout the range of predicted variables. Therefore, it suggested that the combined model might be used on broad regional or perhaps provincial level data sets.

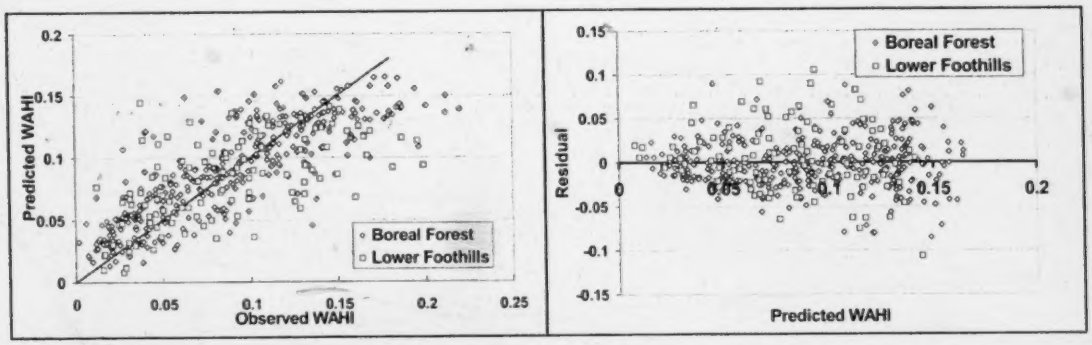

Figure 3.10 Combined data - actual weighted annual height increment (WAHI) versus predicted WAHI and residual plots of the predicted WAHI

3.2 Height increment model formation for juvenile understory spruce trees

This section is an analysis of height increment of understory white spruce less than 1.3m in height. In the following discussion these trees will be defined as "juvenile".

In the Boreal sub-region a total of 1207 living juvenile understory white spruce were sampled and of those 1113 had a height increment measurement taken. In the Lower Foothills sub-region a total of 347 living juvenile understory white spruce were sampled and of those 292 had a height increment measurement taken. A regression analysis of weighted annual height increment (WAHI) versus potential explanatory factors was completed for both regions.

3.2.1 Results - Boreal sub-region

In the Boreal sub-region, there was little relationship between explanatory variables and juvenile WAHI (Table 3.10). The strongest relationship was with coniferous spacing factor with a weak R^2 value of 0.1560. RCL had a poor relationship with juvenile WAHI ($R^2 = 0.1133$), which was significantly weaker than the relationship observed for understory white spruce greater than 1.3m (Table 3.5). Therefore, due to the weakness of these results it was not possible to develop a reasonable model for predicting Boreal sub-region WAHI for juvenile understory white spruce based on the explanatory factors collected in this study.

Table 3.10 Boreal sub-region - regression analysis of WAHI versus explanatory variables for juvenile trees

Model	Equations and Variables for Predicting WAHI	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Individual Understory White Spruce Characteristics								
1	X = Understory Tree Height $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0621 0.00586	0.0590 0.00084	0.0652 0.0109	Y Y	0.0047	0.00084
2	X = Understory Height to Live Crown $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0742 -0.0346	0.0711 -0.0448	0.0774 -0.0245	Y Y	0.0432	0.00080
3	X = Understory Crown Length $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0566 0.0318	0.0540 0.0244	0.0592 0.0391	Y Y	0.0741	0.00080
4	X = Understory Relative Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.0417 0.0520	0.0374 0.0434	0.0459 0.0607	Y Y	0.1133	0.00075
5	X = Age at Stump Height $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.0932 -0.2061	0.0869 -0.2450	0.0994 -0.1672	Y Y	0.0993	0.00076
Competition Variables								
6	X = Overstory Crown Closure $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0708 -0.0002	0.0682 -0.00027	0.0733 -0.00013	Y Y	0.0269	0.00082
7	X = Understory Crown Closure at 0.3m $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0516 0.000275	0.0478 0.000204	0.0555 0.000346	Y Y	0.0494	0.00080
8	X = Understory Crown Closure at 1.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0611 0.000569 -0.00001	0.0568 0.00012 -0.00002	0.0654 0.00102 -3.45E-06	Y Y Y	0.0074	0.00083
9	X = Overstory Coniferous Density / Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0671 -8.64E-06	0.0653 -0.00001	0.0689 -5.95E-06	Y Y	0.0347	0.00081
10	X = Overstory Basal Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0732 -0.00053	0.0708 -0.00064	0.0756 -0.00041	Y Y	0.0656	0.00078
11	X = Overstory Coniferous Basal Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.0680 -0.00104	0.0662 -0.00128	0.0698 -0.0008	Y Y	0.0603	0.00079
12	X = Overstory Tree Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0430 0.1212 -0.1055	0.0349 0.0649 -0.1892	0.0510 0.1775 -0.0217	Y Y Y	0.1219	0.00078
13	X = Overstory Coniferous Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0207 0.0957 -0.0454	0.00566 0.041 -0.0861	0.0357 0.1503 -0.00466	Y Y Y	0.1560	0.00075
14	X = Overstory Deciduous Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.0457 0.1048 -0.0928	0.0381 0.0549 -0.1641	0.0534 0.1546 -0.0215	Y Y Y	0.1011	0.00080

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)

3.2.2 Results - Lower Foothills sub-region

In the Lower Foothills sub-region, the relationships between juvenile WAHI and the explanatory factors were stronger than the results for the Boreal sub-region (Table 3.11). With an R^2 of 0.6178, overstory tree spacing factor was the explanatory variable with the strongest relationship with juvenile WAHI (Model 12 - Table 3.11). Relative crown length and stump height age both showed potentially useful relationships with WAHI. These results were satisfactory for proceeding with the development of a multiple regression model for predicting juvenile WAHI.

Several multiple regression models for predicting WAHI were analyzed (Figure 3.12). Selected potential candidate variables for incorporation into the final model were stump height age, relative crown length, overstory tree spacing factor, coniferous spacing factor, and deciduous spacing factor.

The final selected model (Model 2) was:

$$\text{Predicted WAHI} = 0.0481*SAGE^{-0.1619}+0.2363*SF - 0.0928*SF^2 \quad (4)$$

where

SAGE – Stump Height Age

SF – Overstory Tree Spacing Factor

This model was chosen due to the relatively high R^2 value of 0.6987 and all coefficients were significant at a 95% confidence interval. Some models (for instance 7) had a higher R^2, but not all coefficients were significant.

When equation 4 was used to predict WAHI (Figure 3.11), the trend was promising as a higher measured WAHI generally resulted in a higher predicted WAHI. The banding (or grouping) of the points in Figure 3.11 was caused by the strong influence tree spacing factor had on the relationship. For example, all 21 data points that predicted a WAHI greater than 0.16 (Figure 3.11), come from only two plots - in the same stand. Furthermore, these 21 points are from the only plot with a tree spacing factor greater than 0.4 (Table 3.13). Although a lack of sampling points meant the model should be used with caution, it appeared to give a reasonable prediction of juvenile WAHI in the Lower Foothills sub-region.

Table 3.11 Lower Foothills sub-region - regression analysis of WAHI versus explanatory variables for juvenile trees

Model	Equations and Variables for Predicting WAHI	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Individual Understory White Spruce Characteristics								
1	X = Understory Tree Height	B0	0.0641	0.0541	0.0740	Y	0.0418	0.00170
	$= B0 + B1 \cdot X$ (Linear)	B1	0.0294	0.0131	0.0456	Y		
2	X = Understory Height to Live Crown	B0	0.0948	0.0871	0.1026	Y	0.0721	0.00165
	$= B0 + B1 \cdot X$ (Linear)	B1	-0.0685	-0.0969	-0.0401	Y		
3	X = Understory Crown Length	B0	0.0483	0.0407	0.0560	Y	0.2453	0.00134
	$= B0 + B1 \cdot X$ (Linear)	B1	0.0990	0.0790	0.1191	Y		
4	X = Understory Relative Crown Length	B0	0.00502	-0.00931	0.0194	N	0.2839	0.00127
	$= B0 + B1 \cdot X$ (Linear)	B1	0.1276	0.1042	0.1510	Y		
5	X = Age at Stump Height	B0	0.1214	0.1092	0.1335	Y	0.3036	0.00171
	$= B0 \cdot X^{B1}$ (Power)	B1	-0.2627	-0.3366	-0.1888	Y		
Competition Variables								
6	X = Overstory Crown Closure	B0	0.1286	0.1182	0.1389	Y	0.2618	0.00131
	$= B0 + B1 \cdot X$ (Linear)	B1	-0.00118	-0.00141	-0.00095	Y		
7	X = Understory Crown Closure at 0.3m	B0	0.1539	0.1197	0.1880	Y	0.3264	0.0012
	$= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B1	-0.00403	-0.00525	-0.00282	Y		
		B2	0.000037	0.000028	0.000047	Y		
8	X = Understory Crown Closure at 1.3m	B0	0.0933	0.0806	0.1060	Y	0.0239	0.00174
	$= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B1	-0.00168	-0.00295	-0.00041	Y		
		B2	0.000022	5.74E-06	0.000039	Y		
9	X = Overstory Coniferous Density / Ha	B0	0.0802	0.0753	0.0851	Y	0.0022	0.00177
	$= B0 + B1 \cdot X$ (Linear)	B1	-0.00002	-0.00006	0.000027	N		
10	X = Overstory Basal Area/Ha	B0	0.0993	0.0925	0.1061	Y	0.1614	0.00149
	$= B0 + B1 \cdot X$ (Linear)	B1	-0.00082	-0.00104	-0.00061	Y		
11	X = Overstory Coniferous Basal Area/Ha	B0	0.0803	0.0754	0.0852	Y	0.0040	0.00177
	$= B0 + B1 \cdot X$ (Linear)	B1	-0.00029	-0.00083	0.000245	N		
12	X = Overstory Tree Spacing Factor	B0	0.0331	0.0258	0.0405	Y	0.6178	0.00076
	$= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B1	0.2602	0.2181	0.3024	Y		
		B2	-0.103	-0.1262	-0.0798	Y		
13	X = Overstory Coniferous Spacing Factor	B0	0.0712	-0.0754	0.2179	N	0.1831	0.00163
	$= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B1	-0.0361	-0.7263	0.6541	N		
		B2	0.0442	-0.5024	0.5909	N		
14	X = Overstory Deciduous Spacing Factor	B0	0.0338	0.0264	0.0413	Y	0.6074	0.00078
	$= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B1	0.2519	0.2096	0.2942	Y		
		B2	-0.0984	-0.1217	-0.0752	Y		

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)

Table 3.12 Lower Foothills sub-region - multiple regression models predicting weighted annual height increment

Model	Equation for Predicting Weighted Annual Height Increment	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
1	$=B0 \cdot SAge^{B1} + B2 \cdot RCL$	B0	0.0388	0.0155	0.0622	Y	0.4663	0.00131
		B1	-0.6777	-1.3611	0.00563	N		
		B2	0.1153	0.0839	0.1467	Y		
2	$=B0 \cdot SAge^{B1} + B2 \cdot SF + B3 \cdot SF^2$	B0	0.0481	0.0323	0.0639	Y	0.6987	0.00084
		B1	-0.1619	-0.2870	-0.0367	Y		
		B2	0.2363	0.1834	0.2892	Y		
		B3	-0.0928	-0.1206	-0.0649	Y		
3	$=B0 + B1 \cdot RCL + B2 \cdot SF + B3 \cdot SF^2$	B0	0.00576	-0.00548	0.0170	N	0.6656	0.00067
		B1	0.0617	0.0416	0.0817	Y		
		B2	0.2135	0.1712	0.2558	Y		
		B3	-0.0827	-0.1054	-0.0600	Y		
4	$=B0 \cdot SAge^{B1} + B2 \cdot RCL + B3 \cdot SF + B4 \cdot SF^2$	B0	0.00965	-0.0107	0.0300	N	0.7398	0.00073
		B1	-0.4230	-1.5388	0.6927	N		
		B2	0.0683	0.0416	0.0949	Y		
		B3	0.2000	0.1485	0.2516	Y		
		B4	-0.0772	-0.1039	-0.0505	Y		
5	$=B0 \cdot SAge^{B1} + B2 \cdot SFCON + B3 \cdot SFCON^2 + B4 \cdot SFDEC + B5 \cdot SFDEC^2$	B0	0.0946	-0.0172	0.2064	N	0.7035	0.00083
		B1	-0.0767	-0.1979	0.0445	N		
		B2	-0.3373	-0.8704	0.1958	N		
		B3	0.2911	-0.1325	0.7147	N		
		B4	0.2385	0.1857	0.2913	Y		
		B5	-0.0942	-0.122	-0.0664	Y		
6	$=B0 + B1 \cdot RCL + B2 \cdot SFCON + B3 \cdot SFCON^2 + B4 \cdot SFDEC + B5 \cdot SFDEC^2$	B0	-0.0443	-0.1408	0.0523	N	0.6717	0.00066
		B1	0.0665	0.0460	0.0870	Y		
		B2	0.0751	-0.3690	0.5193	N		
		B3	-0.0261	-0.3777	0.3254	N		
		B4	0.2085	0.1661	0.2508	Y		
		B5	-0.0807	-0.1034	-0.0581	Y		
7	$=B0 \cdot SAge^{B1} + B2 \cdot RCL + B3 \cdot SFCON + B4 \cdot SFCON^2 + B5 \cdot SFDEC + B6 \cdot SFDEC^2$	B0	0.0289	-0.0763	0.1340	N	0.7503	0.00071
		B1	-0.1197	-0.6684	0.4291	N		
		B2	0.0783	0.0517	0.1048	Y		
		B3	-0.2837	-0.7725	0.2052	N		
		B4	0.2603	-0.1279	0.6486	N		
		B5	0.1986	0.1477	0.2494	Y		
		B6	-0.0776	-0.1039	-0.0513	Y		

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)
Note: RCL – Relative Crown Length, Sage - Stump Height Age, SF-Overstory Tree Spacing Factor, SFCON – Overstory Coniferous Tree Spacing Factor, SFDEC – Overstory Deciduous Tree Spacing Factor

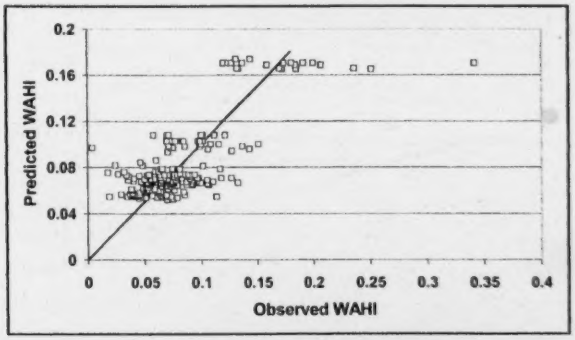

Figure 3.11 Lower Foothills sub-region - actual weighted annual height increment (WAHI) versus predicted WAHI based on the selected final multiple regression model

Table 3.13 Lower Foothills sub-region - occurrence of tree spacing factor by plot and individual understory white spruce

Tree Spacing Factor Groupings	Number of Plots	Number of Individual Understory White Spruce
0-0.1	1	35
0.1-0.2	42	163
0.2-0.3	11	42
0.3-0.4	1	0
0.7-0.8	1	12
1.7-1.8	1	9
Total	57	261

3.2.3 Height increment and site quality

No study of height growth is complete without addressing the relationship between site quality and height increment. The correlation between site quality and height increment for free growing trees is widely recognized (Davis and Johnson, 1987). Although understory trees are not free growing it is reasonable to expect site quality to impact understory tree height increment as well. Therefore, it is important to examine potential observed differences due to site quality. During this project no direct measurements of site quality were taken. However, two indirect methods (site index and AVI - timber productivity rating) were available for evaluating site quality.

3.2.3.1 Height increment and Alberta Vegetative Inventory - timber productivity rating

In the Alberta Vegetative Inventory (AVI), each stand is assigned a coarse value of site quality called timber productivity rating (TPR). On forested stands one of three TPR values is possible:

- Fair (lowest site quality)
- Medium
- Good (highest site quality)

In the Boreal sub-region, 41 stands had a TPR of "good" while 12 were rated as "medium". WAHI showed no apparent difference between the Medium and Good TPR classes. This interpretation was supported by the substantial overlap of the 95% confidence intervals for WAHI (Table 3.14). This is consistent with studies that have shown that white spruce are tolerant of low nutrient levels (Delong et al. 1997). This suggested that nutrient levels are not as constraining to understory spruce height increment as other factors.

In the Lower Foothills sub-region, an analysis of TPR was not feasible, because 20 of the 23 stands sampled had a "medium" TPR. Only two stands (with a total of nine understory white spruce greater than 1.3m) were given a "fair" rating, while only one stand was given a TPR of "good" (no understory white spruce sampled).

Table 3.14 Boreal sub-region - comparison between AVI timber productivity rating and weighted annual height increment (WAHI)

AVI TPR	Understory White Spruce Sampled	Mean WAHI	95% Confidence Interval of the Mean	
			Lower Limit	Upper Limit
Medium	129	0.0899	0.0817	0.0981
Good	405	0.0828	0.0777	0.0879

3.2.3.2 Site Index and WAHI

In the Boreal sub-region, stand site index values did not have a significant impact on WAHI (Figure 3.12). This suggested that site index was not a reliable factor to predict understory white spruce height growth. There were a number of complicating factors that could have contributed to these results including:

- only 39 of the total of 53 stands sampled allowed an SI estimation since appropriate site trees were not available
- of the 39 stands with an SI estimation, 24 were based on the results of measurements from only 1 or 2 site trees (if possible 3 were to be measured)
- white spruce site tree measurements were suspect because it was likely that the majority of overstory white spruce were not free-growing for their lifespan, resulting in potential underestimates of site index (Davis and Johnson, 1987).

In the Lower Foothills sub-region, WAHI and stand site index showed an interesting positive trend (Figure 3.12). However, Table 3.15 demonstrated this trend was not significant and its inclusion could not be justified for this study.

Initially, SI was anticipated to have an important impact on the height growth of understory white spruce. However, the results suggested that SI did not have as significant an impact as competition factors. As spruce trees grow and the impact from competitive variables decreased, it was expected that SI becomes more important for estimating the height growth. Therefore, it was still expected that an overstory model of white spruce growth would include site index as an important component.

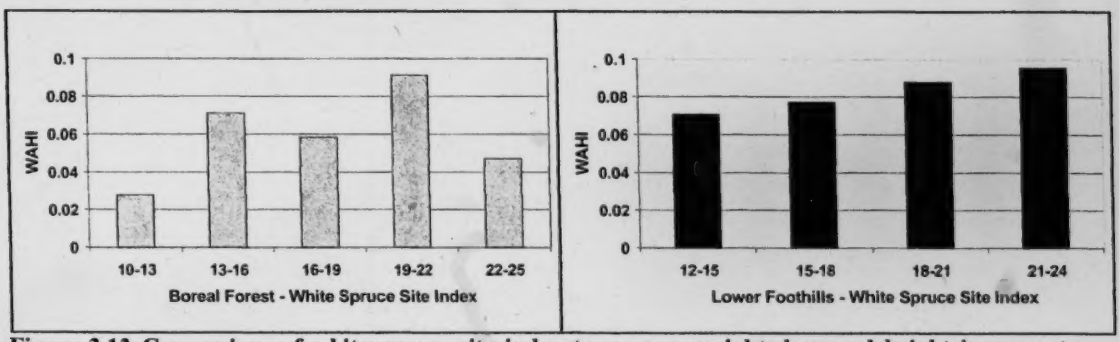

Figure 3.12 Comparison of white spruce site index to average weighted annual height increment (WAHI)

Table 3.15 Lower Foothills sub-region - mean weighted annual height increment (WAHI) by Site Index Category

Site Index Range	Number of Understory White Spruce Sampled	Mean WAHI	95% Confidence Interval of the Mean	
			Lower Limit	Upper Limit
12 – 15	29	0.0681	0.0500	0.0861
15 –18	44	0.0765	0.0649	0.0882
18 – 21	34	0.0863	0.0624	0.0110
21 – 24	39	0.0934	0.0779	0.1088

3.2.4 Height increment and light transmittance (DIFN)

In the Boreal sub-region, only 66 plots of the total of 159 plots had light measurements taken. Of those 66 plots 54 had an estimated DIFN of less than 0.3 (or 30% light transmittance) (Figure 3.13). Similarly in the Lower Foothills sub-region, 51 of the 69 plots with light measurements taken had a DIFN below 0.3 (Figure 3.15). These results are consistent with Constabel and Lieffers (1996) who showed light transmittance in pure aspen and mixedwood stands to be predominantly less than 30% light transmittance during the summer months. Some studies suggest understory white spruce achieve close to maximum potential growth at 40 to 45% light transmittance (Lieffers and Stadt 1994, Wright 2001). However, there is also evidence that there is some increase in growth up to full 100% light transmittance (Comeau et al. 1993). Regardless, the majority of understory white spruce trees in both regions were experiencing significant light deprivation.

The results from both regions appeared to confirm that maximum understory white spruce growth requires at least 40 to 45% light transmittance (Lieffers and Stadt 1994). In the Boreal sub-region, when light transmittance was 40% (or 0.4 DIFN) or greater, average WAHI was 0.121,

compared to below 40% light transmittance average WAHI was 0.065 (Figure 3.13). Similarly in the Lower Foothills sub-region, when light transmittance was 40% or greater, average WAHI was 0.125, whereas below 40% light transmittance average WAHI was 0.084 (Figure 3.15).

The same trend occurred when AAHI was the dependent variable. In the Boreal sub-region, when light transmittance was 40% (or 0.4 DIFN) or greater, average AAHI was 20cm, compared to below 40% light transmittance average AAHI was 11cm. In the Lower Foothills sub-region, when light transmittance was 40% or greater, average AAHI was 24cm, whereas below 40% light transmittance average AAHI was 17cm. When considering these results it was important to be mindful of the relatively small number of plots sampled with a light transmittance greater than 40%.

A regression analysis using DIFN as the explanatory variable for AAHI and WAHI was done. Although the relationships were weak, a clear trend emerges where increased DIFN resulted in increased height increments. In the Boreal sub-region, when DIFN was plotted versus AAHI and WAHI the R^2 values were 0.136 and 0.198 respectively (Figure 3.14). Similarly in the Lower Foothills sub-region the results showed an R^2 of 0.059 for AAHI and 0.168 for WAHI (Figure 3.16). These trends were not strong enough to warrant including DIFN as an explanatory variable in the multiple variable regression WAHI model. In addition, DIFN would be of limited use for a height growth model because as a measure of competition it is more difficult to measure then other variables (such as spacing factor or density).

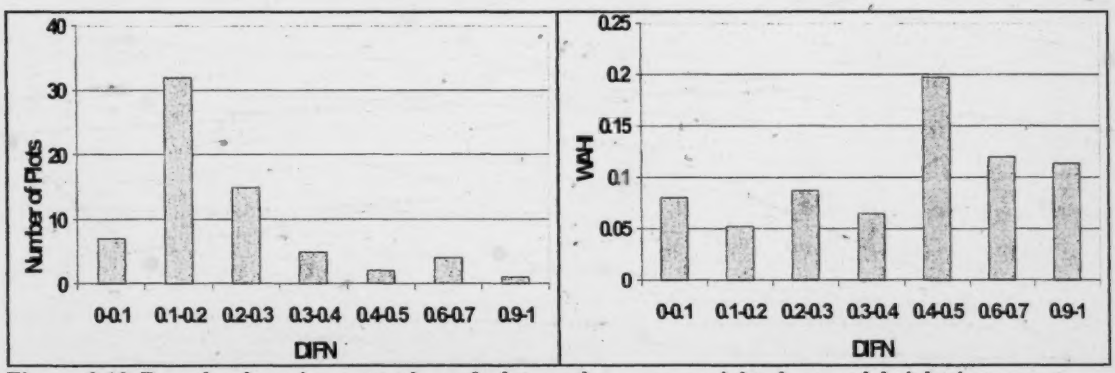

Figure 3.13 Boreal sub-region - number of plots and average weighted annual height increment (WAHI) in each light transmittance (DIFN) category

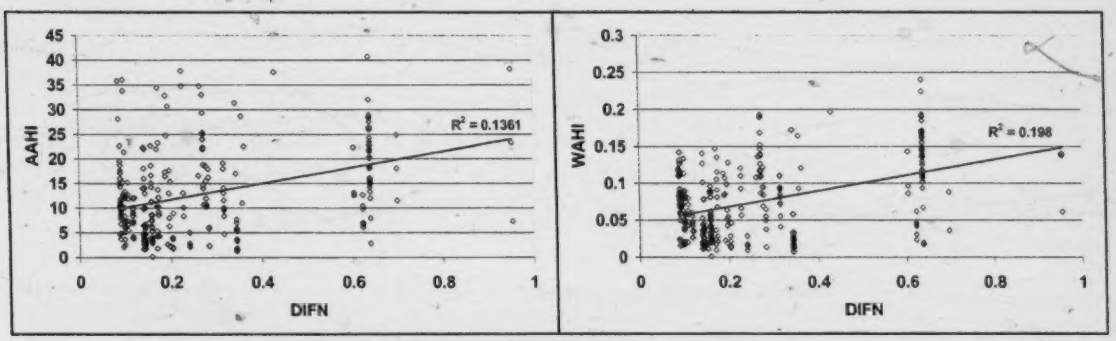

Figure 3.14 Boreal sub-region – light transmittance (DIFN) versus annual average height increment (AAHI) and weighted annual height increment (WAHI)

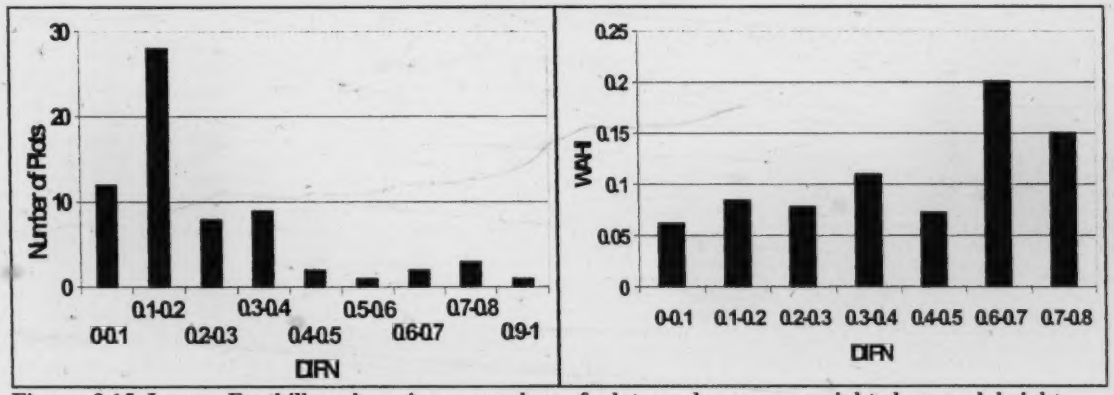

Figure 3.15 Lower Foothills sub-region - number of plots and average weighted annual height increment (WAHI) in each light transmittance (DIFN) category

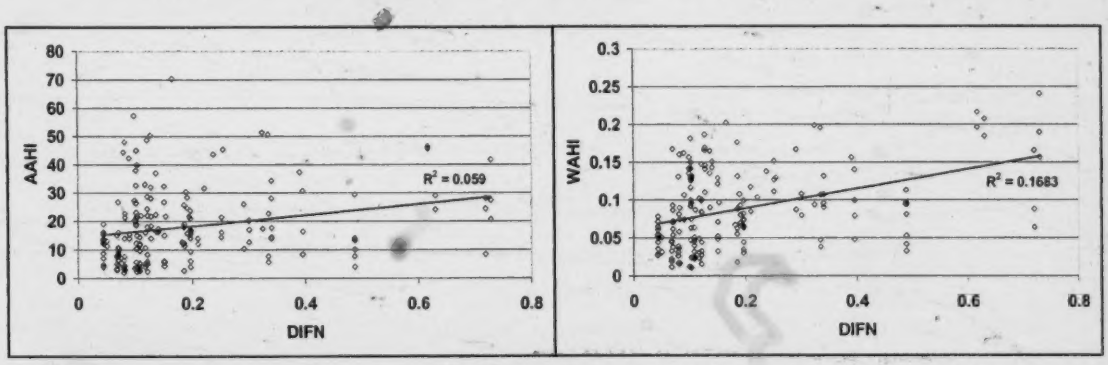

Figure 3.16 Lower Foothills sub-region – light transmittance (DIFN) versus annual average height increment (AAHI) and weighted annual height increment (WAHI)

3.3 Predicting relative crown length

In this study relative crown length (RCL) was the most important factor in the equations used for predicting WAHI. This is consistent with other studies that have shown an increase in seedling growth associated with an increase in needle biomass (Comeau et al. 1993). Although RCL is a tree attribute that is not typically measured during field sampling, the results suggested that any sampling program (designed to predict understory spruce height growth) should include measurement of live crown length.

When using the WAHI model it was important to remember that RCL will likely change as a tree ages. Therefore to ensure reasonable estimates of height increment it was important to estimate changes in RCL over time. Through regression analysis a predictive model of RCL was produced. The model should be considered only applicable for understory white spruce greater than 1.3 tall.

3.3.1 Boreal sub-region model

In the Boreal sub-region the variable with the strongest relationship with RCL was BAGE with an R^2 of 0.4900 (Table 3.16). A number of competition variables had a moderately strong relationship with RCL: coniferous tree spacing factor, deciduous tree spacing factor, total tree spacing factor, understory crown closure at stump height, overstory crown closure, and understory white spruce density. All competition variables either had a quadratic or linear relationship with RCL.

Because of its strong relationship with RCL, BAGE was used as the starting variable for formulating multiple regression models (Table 3.17). The two-variable models with the strongest relationship to RCL included the explanatory factors of BAGE (power form) and coniferous spacing factor (quadratic form - Model 10 - Table 3.17). Model 10 improved the prediction of RCL by increasing the R^2 from 0.4900 to 0.6006. As deciduous spacing factor is a complement to coniferous spacing factor an attempt was made to fit a three variable model by adding deciduous spacing factor to Model 10; this resulted in Model 13, which improved RCL predictions to an R^2 of 0.6498 with all coefficients showing significance (Table 3.17).

Table 3.16 Boreal sub-region - regression models for predicting relative crown length by individual explanatory factors

Model	Equations and Variables for Predicting Relative Crown Length	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Individual Understory White Spruce Characteristics								
1	X = Understory Tree Height $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.6936 -0.1360	0.6640 -0.1664	0.7233 -0.1057	Y Y	0.08522	0.0324
2	X = Understory Crown Length $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.5367 0.0978	0.5191 0.0682	0.5544 0.1274	Y Y	0.05217	0.0336
3	X = Understory Diameter Breast Height $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.6269 -0.0729	0.6080 -0.0945	0.6458 -0.0512	Y Y	0.04881	0.0337
4	X = Age at Breast Height $= B0 \cdot X^{B1}$ (Power)	B0 B1	0.8018 -0.1236	0.7684 -0.1399	0.8351 -0.1072	Y Y	0.49001	0.0243
Competition Variables								
5	X = Overstory Crown Closure $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.8019 -0.00952 0.000075	0.7709 -0.0113 0.000053	0.8330 -0.00772 0.000096	Y Y Y	0.24789	0.0267
6	X = Understory Crown Closure at 0.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.3814 0.0104 -0.00009	0.3561 0.00886 -0.00011	0.4068 0.0120 -0.00007	Y Y Y	0.26713	0.0260
7	X = Understory Crown Closure at 1.3m $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.4770 0.0121 -0.00017	0.4563 0.0102 -0.0002	0.4977 0.0140 -0.00014	Y Y Y	0.15400	0.0300
8	X = Overstory Deciduous Density / Ha $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.5653 2.92E-06 1.03E-09	0.5414 -0.00001 -2.88E-10	0.5891 0.000018 2.35E-09	Y N N	0.02632	0.0345
9	X = Overstory Coniferous Density / Ha $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.6576 -0.00041 1.65E-07	0.6420 -0.00047 1.32E-07	0.6732 -0.00035 1.98E-07	Y Y Y	0.19629	0.0285
10	X = Overstory Basal Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.7078 -0.00545	0.6863 -0.00621	0.7292 -0.00468	Y Y	0.18580	0.0288
11	X = Overstory Coniferous Basal Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.6282 -0.00884	0.6138 -0.0103	0.6425 -0.00736	Y Y	0.13896	0.0305
12	X = Overstory Deciduous Area/Ha $= B0 + B1 \cdot X$ (Linear)	B0 B1	0.6341 -0.00305	0.6145 -0.00389	0.6536 -0.00221	Y Y	0.05609	0.0334
13	X = Understory Sw Density/ha $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.4802 0.000031 -6.44E-10	0.4608 0.000025 -9.70E-10	0.4996 0.000038 -3.18E-10	Y Y Y	0.21255	0.0279
14	X = Overstory Tree Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.3081 1.6493 -1.3179	0.2539 1.2437 -1.8813	0.3623 2.0550 -0.7545	Y Y Y	0.26504	0.0267
15	X = Overstory Coniferous Tree Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.2697 0.7062 -0.2835	0.2071 0.4701 -0.4642	0.3324 0.9423 -0.1028	Y Y Y	0.32787	0.0243
16	X = Overstory Deciduous Tree Spacing Factor $= B0 + B1 \cdot X + B2 \cdot X^2$ (Quadratic)	B0 B1 B2	0.4300 0.7639 -0.4874	0.3901 0.5261 -0.7426	0.4699 1.0018 -0.2322	Y Y Y	0.11341	0.0318

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)

Table 3.17 Boreal sub-region - multiple regression models predicting relative crown length

Model	Equation for Predicting Relative Crown Length	Coef	Estimate	95% Confidence Interval		Sig	R^2	Mean Square Error
				Lower Limit	Upper Limit			
Two-Variable Model								
1	$=B0 \cdot BAge^{B1} + B2 \cdot OCC + B3 \cdot OCC^2$	B0	0.8717	0.8346	0.9088	Y	0.5340	0.0223
		B1	-0.0689	-0.0864	-0.0515	Y		
		B2	-0.00661	-0.00887	-0.00436	Y		
		B3	0.000058	0.000032	0.000084			
2	$=B0 \cdot BAge^{B1} + B2 \cdot UCCS + B3 \cdot UCCS^2$	B0	0.6067	0.5556	0.6577	Y	0.5573	0.0212
		B1	-0.1112	-0.1311	-0.0913	Y		
		B2	0.00652	0.00476	0.00828	N		
		B3	-0.00005	-0.00007	-0.00003	N		
3	$=B0 \cdot BAge^{B1} + B2 \cdot UCCB + B3 \cdot UCCB^2$	B0	0.7211	0.6766	0.7656	Y	0.5139	0.0233
		B1	-0.1132	-0.1311	-0.0952	Y		
		B2	0.00579	0.00366	0.00792	Y		
		B3	-0.00009	-0.00012	-0.00006			
4	$=B0 \cdot BAge^{B1} + B2 \cdot CON\_HA + B3 \cdot CON\_HA^2$	B0	0.7977	0.7677	0.8277	Y	0.5637	0.0209
		B1	-0.085	-0.101	-0.0691	Y		
		B2	-0.0003	-0.00036	-0.00023	Y		
		B3	1.11E-07	7.58E-08	1.47E-07	Y		
5	$=B0 \cdot BAge^{B1} + B2 \cdot BA\_HA$	B0	0.8112	0.7796	0.8427	Y	0.5152	0.0232
		B1	-0.0867	-0.1055	-0.068	Y		
		B2	-0.00266	-0.00358	-0.00175	Y		
6	$=B0 \cdot BAge^{B1} + B2 \cdot BA\_CON$	B0	0.804	0.7731	0.835	Y	0.5409	0.0219
		B1	-0.1005	-0.1161	-0.0848	Y		
		B2	-0.00653	-0.00807	-0.005	Y		
7	$=B0 \cdot BAge^{B1} + B2 \cdot BA\_DEC$	B0	0.803	0.7697	0.8363	Y	0.4907	0.0243
		B1	-0.1188	-0.1378	-0.0998	Y		
		B2	-0.00043	-0.00131	0.000462	N		
8	$=B0 \cdot BAge^{B1} + B2 \cdot USWD + B3 \cdot USWD^2$	B0	0.726	0.6672	0.7848	Y	0.5048	0.0237
		B1	-0.1008	-0.1222	-0.0795	Y		
		B2	6.30E-06	-2.48E-06	0.000015	N		
		B3	4.71E-11	-3.22E-10	4.16E-10	N		
9	$=B0 \cdot BAge^{B1} + B2 \cdot SF + B3 \cdot SF^2$	B0	0.5823	0.5059	0.6587	Y	0.5598	0.0216
		B1	-0.0981	-0.1211	-0.0752	Y		
		B2	0.7043	0.2797	1.1289	Y		
		B3	-0.3486	-0.9158	0.2186	N		
10	$=B0 \cdot BAge^{B1} + B2 \cdot SFCON + B3 \cdot SFCON^2$	B0	0.4736	0.3954	0.5517	Y	0.6006	0.0196
		B1	-0.116	-0.1512	-0.0808	Y		
		B2	0.5236	0.25	0.7971	Y		
		B3	-0.209	-0.4199	0.0018	N		
11	$=B0 \cdot BAge^{B1} + B2 \cdot SFDEC + B3 \cdot SFDEC^2$	B0	0.7086	0.6494	0.7679	Y	0.5165	0.0234
		B1	-0.1192	-0.1376	-0.1009	Y		
		B2	0.2749	0.0419	0.5079	Y		
		B3	-0.1013	-0.3435	0.1409	N		
Three-Variable Model								
12	$=B0 \cdot BAge^{B1} + B2 \cdot BA\_CON + B3 \cdot BA\_DEC$	B0	0.8119	0.7819	0.8419	Y	0.5546	0.0213
		B1	-0.0771	-0.0948	-0.0594	Y		
		B2	-0.00785	-0.00948	-0.00623	Y		
		B3	-0.002	-0.00289	-0.0011	Y		
13	$=B0 \cdot BAge^{B1} + B2 \cdot SFDEC + B3 \cdot SFDEC^2 + B4 \cdot SFCON + B5 \cdot SFCON^2$	B0	0.2427	0.1482	0.3371	Y	0.6498	0.0174
		B1	-0.1165	-0.1822	-0.0508	Y		
		B2	0.5604	0.3452	0.7756	Y		
		B3	-0.3382	-0.5706	-0.1058	Y		
		B4	0.7182	0.4561	0.9803	Y		
		B5	-0.3367	-0.5382	-0.1353	Y		

Coef - Coefficients, Sig - Coefficient Significant at 95% Confidence (Y-Yes, N-No)

Note: BAge-Breast Height Age, BA-Basal Area, CON_HA – Overstory Coniferous Density, SF-Overstory Tree Spacing Factor, SFCON – Overstory Coniferous Tree Spacing Factor, SFDEC – Deciduous Spacing Factor, USWD – Understory White Spruce Density, UCCS – Understory Crown Closure at Stump Height

The final selected model for predicting relative crown length in the Boreal sub-region is (Model 13 - Table 3.17):

Predicted RCL=

$$0.2427 \cdot BAGE^{-0.1165} + 0.5604 \cdot SFDEC + -0.3382 \cdot SFDEC^2 + 0.7182 \cdot SFCON + -0.3367 \cdot SFCON^2 \quad (5)$$

Where:

BAGE – Breast height age
SFDEC – Deciduous spacing factor
SFCON – Coniferous spacing factor

The relationship between BAGE and RCL was in the power form, showing a general trend of decreased relative crown length as a tree ages (Figure 3.17). This equation could be applied to a wide range of breast height ages from 1 year to 80 years old.

The competition variable with the strongest relationship with RCL was coniferous spacing factor ($R^2 = 0.3279$). The relationship was quadratic, with RCL increasing as coniferous spacing factor increases (Figure 3.17). This is likely due to overstory coniferous trees transmitting a very low percentage of incoming light (between 5% and 11%) compared to overstory deciduous trees (between 14% and 40%) (Lieffers and Stadt 1993). Therefore, with more coniferous trees in the overstory less light is transmitted to the understory spruce and less live crown is retained for photosynthesis. SFCON ranged from a minimum of just below 0.2 to a maximum of 1.0. All plots without any coniferous trees in the overstory were assumed to have a coniferous spacing factor of 1.0.

Deciduous spacing factor was weakly correlated to RCL ($R^2 = 0.1134$ -Table 3.16); however, the multiple regression model benefited from its inclusion by improving the R^2 value from 0.6006 to 0.6498. When deciduous spacing factor was plotted individually versus RCL (Figure 3.17); the general trend was for RCL to increase as deciduous spacing factor increased. However, above a deciduous spacing factor of 0.7 there was a slight decrease in RCL. This is likely caused by an increase in shrub and herb competition caused by increased light transmittance (Constabel and Lieffers 1996) (Figure 3.8). As with coniferous spacing factor, all plots without any deciduous trees in the overstory were assumed to have a deciduous spacing factor of 1.0.

When model predicted RCL (equation 5) was plotted versus actual RCL the model provided reasonable estimates. While the magnitude of residuals was large, bias was not evident (Figure 3.18).

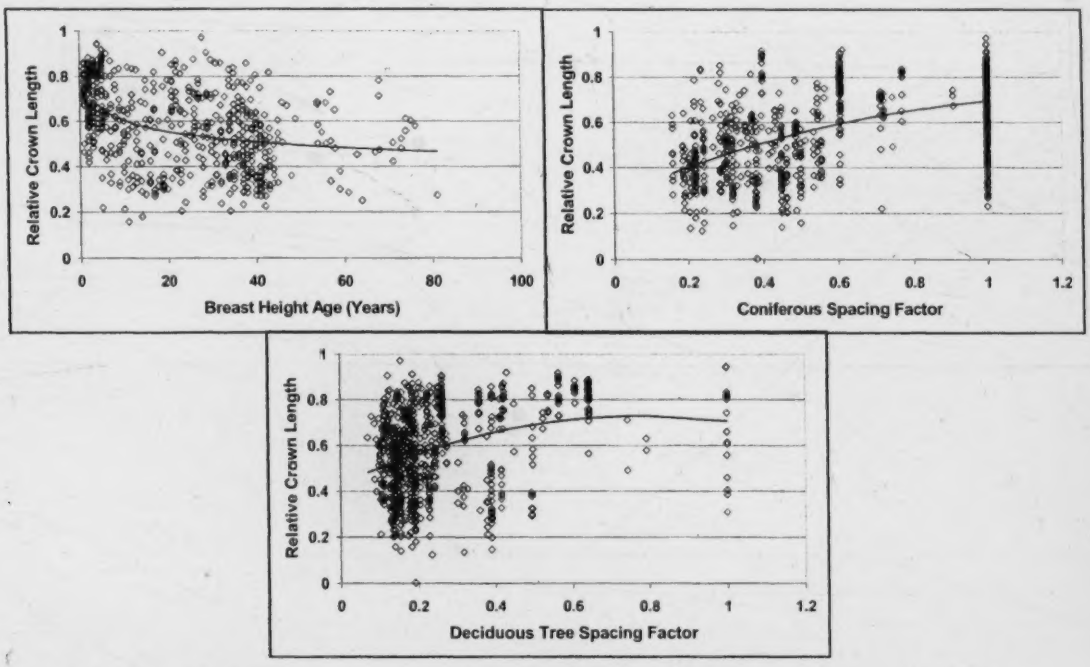

Figure 3.17 Boreal sub-region – regression relationship between understory white spruce relative crown length and individual explanatory factors in the final model

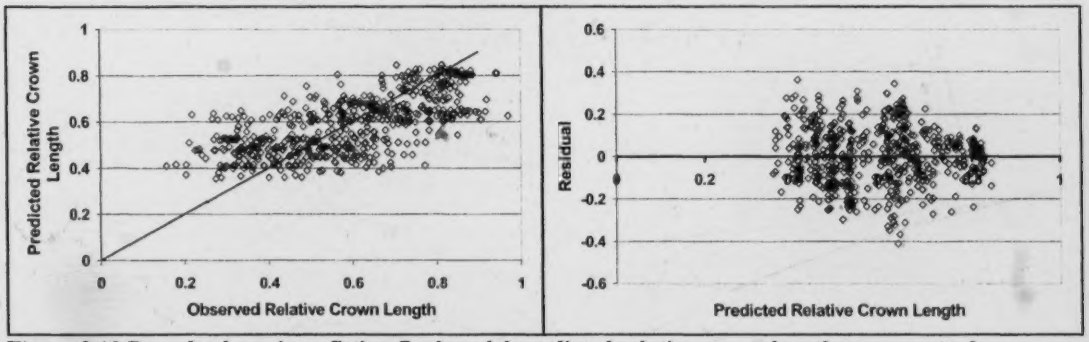

Figure 3.18 Boreal sub-region - fitting final model predicted relative crown length versus actual relative crown length of understory white spruce

3.3.2 Combined model

In section 3.1.8 a model predicting WAHI based on combined data from the Boreal sub-region and Lower Foothills sub-region was produced. To enable the use of this model, RCL was also

predicted by fitting the combined data to Model 13 from Table 3.17 (See Table 3.18 for coefficient 95% Confidence Limits for equation 6).

Predicted RCL=

$$0.1959 \cdot BAge^{-0.1168} + 0.7354 \cdot SFDEC + -0.5553 \cdot SFDEC^2 + 0.8163 \cdot SFCON + -0.4245 \cdot SFCON^2 \quad (6)$$

Table 3.18 Coefficient estimates from fitting combined RCL data to model 13

Coefficient	Coefficient Estimate	95% Confidence Interval of the Mean	
		Lower Limit	Upper Limit
B0	0.1959	0.1055	0.2862
B1	-0.1168	-0.1933	-0.0404
B2	0.7354	0.5485	0.9223
B3	-0.5553	-0.7312	-0.3793
B4	0.8163	0.5551	1.0776
B5	-0.4245	-0.6235	-0.2255

As with the model predicting RCL in the Boreal sub-region the range of error in the predicted estimates was quite high. However equation 6 had an R^2 value of 0.5869 with all coefficients significant at 95% confidence and did not show bias in either the Boreal sub-region or Lower Foothills sub-region data points (Figure 3.19). Therefore, this model appeared to be suitable for prediction of RCL in both the Boreal sub-region and Lower Foothills sub-region.

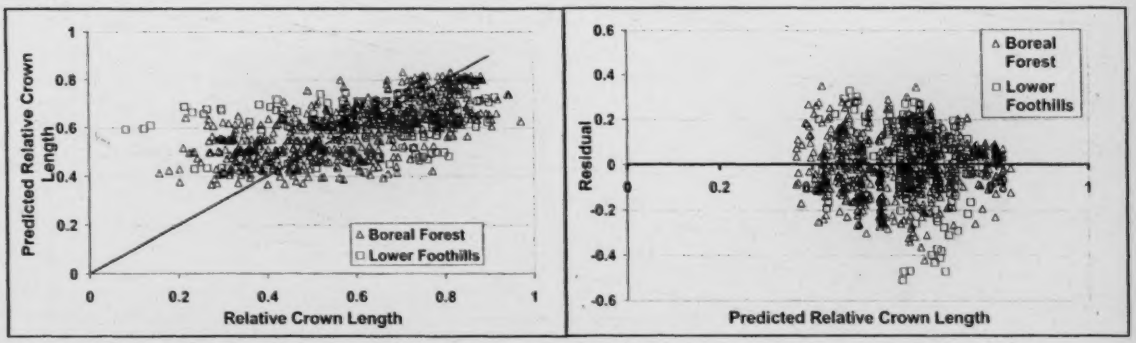

Figure 3.19 Combined data - fitting final model predicted relative crown length versus actual relative crown length of understory white spruce

4 Conclusions

Equations 1 and 5 can be used in conjunction to predict height growth of Boreal sub-region understory white spruce greater than 1.3m tall; equations 3 and 6 can be used in conjunction to predict height growth of understory white spruce greater than 1.3m tall at a broad provincial level. Both sets of equations can be justified based on a statistical and biological perspective and this makes them suitable for use in a growth model such as MGM. In contrast, the model developed for predicting height increment in the Lower Foothills sub-region (equation 2) is of limited use. Problems with achieving an acceptable model for the Lower Foothills sub-region may have been caused by having a smaller sample size, thus the combined model should be used instead. To develop an improved model for the Lower Foothills sub-region another study that focuses specifically on that region and the associated unique issues will need to be done.

As for the relationship between a deciduous canopy and its associated understory white spruce trees, the only definite statement that can be made is that there is no single competitive factor that can be controlled to "guarantee" improved understory white spruce height growth. Rather there is a complex interaction between competitive factors and understory white spruce. However, some other general observations may be made:

1. When comparing the height growth of various sized white spruce trees, relative measurements are more useful than absolute measures (e.g. AAHI versus WAHI).
2. By using RCL, BAGE, and SF a reasonable model for predicting height increment of understory white spruce taller than 1.3m can be built.
3. Of the overstory competition variables, tree spacing factor or coniferous spacing factor appears to have the strongest relationship to height increment growth.
4. The relations between WAHI and explanatory variables were much stronger for understory spruce taller than 1.3m, compared to juvenile white spruce. This suggests that the fixed-area plot approach used in this study does not sufficiently estimate the competition experienced by juvenile trees (those smaller than 1.3m). Measuring competition factors impacting each individual tree might improve predictions.
5. Competition from shrubs and non-woody vegetation appears to impact understory white spruce height growth. However, it is a complex relationship that is affected by the type (deciduous or coniferous) and amount of overstory competition.

6. The usefulness of site index values when predicting height growth of understory white spruce is undetermined.
7. Light transmittance (DIFN) does have an impact on potential understory spruce growth; however, it is only one of many factors which influences white spruce growth.

5 Recommendations for future studies

Three suggestions for future studies are:

1. Use a larger sized plot for overstory measurements than understory measurements. This would give a better representation of the overstory trees that are potentially impacting the understory trees.
2. If possible a stand should be measured prior to the growth period so growth increments can be related to the characteristics of the tree (and/or stand) at the start of the growing period rather than the end.
3. Use a crop tree sampling method, where potential future crop trees are identified. This process may improve relationships, because for a densely populated stand the dying and suppressed trees will not be included in a regression analysis.

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7 Appendices

7.1 Model validation using a growth simulator (MGM)

A model is useful only if it gives reasonable estimates of the dependent variable. An individual tree growth model (MGM) was used to evaluate the models produced in this project. Model validation was done in two ways:

1. The growth projections based on the WAHI and RCL models were compared to the growth projections when the models were not utilized.
2. The WAHI and RCL model projections were compared to the project sample data.

7.1.1 Incorporating WAHI and RCL models into MGM

For correct usage, a model can only be applied to stands showing similar attributes as those sampled to form the model. Therefore, prior to utilizing a model in a growth simulator the formation of the model must be clearly understood. To review from section 3.1.6 the boreal sub-region WAHI and RCL models are to be applied only in the follow instances:

- To understory white spruce:
    - Between 1.3m and 15m tall
    - With a maximum breast height age (BAGE) of 80 years
- To stands with a tree spacing factor (SF) with maximum of 0.65.

Due to the RCL and WAHI models being valid for understory trees only, a site index based model was used to predict height growth for overstory white spruce trees (see below for the decision rules used for assigning an overstory or understory designation).

In MGM, the DBH size of a tree is sometimes used to decide when equations are applied. Thus it was important to understand the distribution of understory white spruce DBH measurements used to produce the WAHI and RCL models. Of the sampled understory spruce greater than 1.3 tall, 96% had a DBH below 10cm (Figure 7.1). This was the basis for applying the WAHI and RCL models only to trees with a DBH less than 10cm. Passed this limit, height increments were estimated with a site index based model.

Although during this study a 10cm DBH was set as the limit for the WAHI and RCL models, conveniently MGM uses a 4.0cm. Interestingly, 83% of the understory white spruce sampled came from trees with a DBH below 4.0cm; therefore this convention is also supportable.

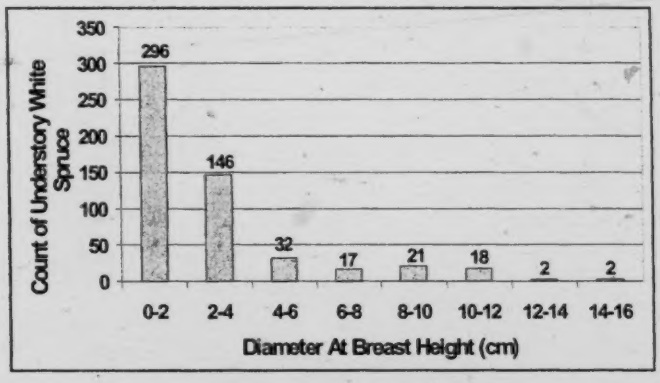

Figure 7.1 Boreal sub-region - number of understory white spruce sampled (with a height increment measurement) by DBH category

All growth projections that utilized the WAHI and RCL models, required all trees in a stand to be identified as being in either the overstory or understory. This designation was important because the model projections were only valid for understory white spruce. Additionally, both the WAHI and RCL models required inputs from the deciduous and coniferous overstory characteristics. The following decision rules were used for assigning an overstory or understory designation throughout the growth projection period:

- All white spruce trees were assumed to be in the understory unless one of the following was true:
    - The tree had a DBH of 10cm or greater
    - The tree had a height equal to or greater than 50% of the average height of the deciduous trees.
    - There were no deciduous trees present in the stand
- All deciduous trees were assumed to be in the overstory

When using the RCL model it is important to be aware that treatments (like thinning) can cause a rapid change in predicted RCL. In these situations, it is acknowledged that the predicted RCL will sometimes change more rapidly than RCL would respond in the field. However, it is expected that this difference (between actual and predicted RCL) should only be significant for a

small number of years and over growth prediction periods of several decades this difference should have a negligible effect on predictions.

7.1.2 Preliminary MGM growth projections

Prior to this study MGM used a method of predicting height growth of understory trees that was based on using a relative increment factor (RF) that utilized predicted maximum site curve increments. The equation used was: Height Increment = Maximum Potential Height Increment (from site curves) * RF.

RF - an adjustment factor based on stand competition derived from basal area (m^2/ha)

In MGM, the height growth of white spruce was projected for six different spruce and aspen density combinations. The Boreal sub-region WAHI and RCL model (equations 1 and 5) results were compared to the RF method estimates (Figure 7.2, Figure 7.3). Plot 1 is pure spruce at 1000/ha. Plots 2 to 6 are mixes, all with spruce at 1000/ha with increasing density of aspen (200, 500, 1500, 4000, and natural).

WAHI and RCL height projections were significantly lower than the RF based estimates, with plots 2 to 6 each showing close to a 5m difference at stand age 40. This will result in a significant difference in the prediction of future stand attributes (like volumes). Another distinction is at stand age 40 the RF method resulted in almost no difference in spruce heights regardless of aspen density; however the RCL and WAHI projections clearly showed a divergence in understory white spruce heights by this age. Obviously, height projections differed significantly depending on the model used.

Upon closer examination it was apparent that the RF method was probably over-predicting understory height growth. Plot 1 represented the growth rate of a pure white spruce stand, thus the estimates are the same in Figure 7.2 and Figure 7.3. Up to stand age 40, the RF projection indicated that all aspen-spruce mixed stands (plots 2 to 6) were growing at the nearly same rate and only slightly lower than the pure spruce plot. However, realistically the WAHI and RCL models showed decreased height growth on the mixed plots.

In addition, compared to the RF method, the WAHI and RCL models predicted age-height relationships that are closer to the averages from field-sampled data (data from this study). To enable comparisons of field age-height relationships to the MGM projections it must be remembered that the MGM scenarios were based on stand age, while the field data was based on breast height age. The MGM scenarios projected a stand age of approximately 20 years (actually 18 years) before the average white spruce tree reaches breast height (1.3m). This means a breast height age of 40 is comparable to a stand age of 60.

The field data showed an average height at breast age 40 between 9.0 and 10.0m (Figure 7.4). This was close to the estimates of 7.5m to just over 10.0m (depending on scenario) for the WAHI and RCL models at a stand age of 60. In comparison, all RF scenarios significantly exceeded 9.5m at a stand age of 60 years.

The RCL and WAHI models seemed to give more realistic estimates of understory white spruce height growth. However, RCL and WAHI did not project as large a difference between scenarios as would be expected (less than 1m at stand age of 40). Another problem was none of the scenarios (using the RCL and WAHI models) project heights anywhere close to the average height potential projections for pure white spruce stands (Plot 1). This was not expected as it has been suggested that in some situations height growth for white spruce growing under an aspen canopy can equal or perhaps exceed that of open grown spruce (Groot, 1999).

Potential reasons why RCL and WAHI may under-predict height growth are:

1. The stands sampled for this study had a relatively small coniferous component in the overstory (20% or less). However, even a small component of overstory white spruce can significantly reduce the resources available to understory white spruce (Constabel and Lieffers, 1996). Therefore, when projecting height growth in stands with no coniferous in the overstory (as in Figure 7.3), the results from WAHI and RCL models could be viewed as a lower bound of the average understory white spruce.
2. When a stand has conditions favourable for white spruce growth, it is likely that the amount of in-growth will increase. This will also increase the number of white spruce showing suppressed height growth. Therefore, differences in average height between stand types will not be as significant as expected. Perhaps a sampling approach that identified "future crop trees" could minimize this effect.

In conclusion, the RCL and WAHI models resulted in more realistic growth projections when compared to the RF model. In particular, RCL and WAHI models appear to project realistic average height growth in stands with denser overstories (1500+ stem/ha). However, height growth may be under-predicted in a stands with a relatively sparse aspen canopy.

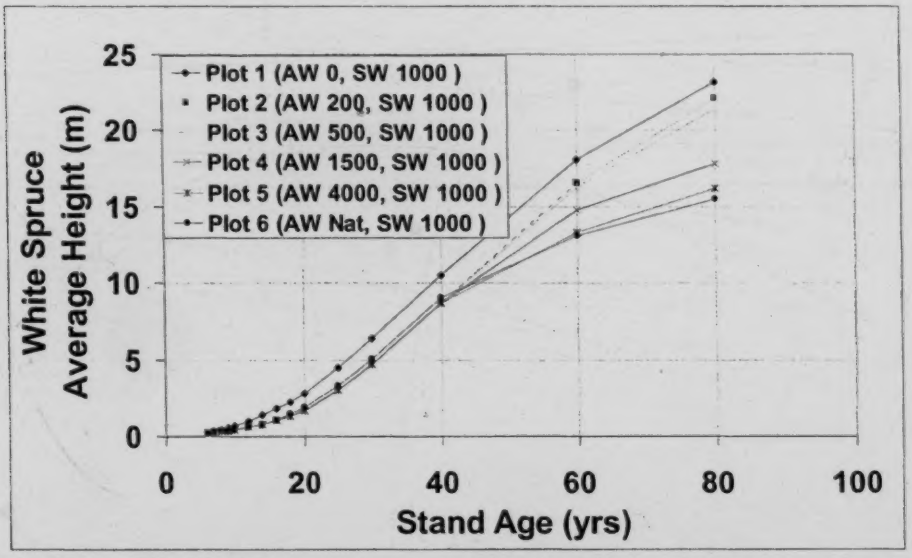

Figure 7.2 Six MGM height growth scenarios with RF method utilized (based on 10cm DBH as maximum for understory trees) - legend indicates starting overstory trembling aspen density and understory white spruce density

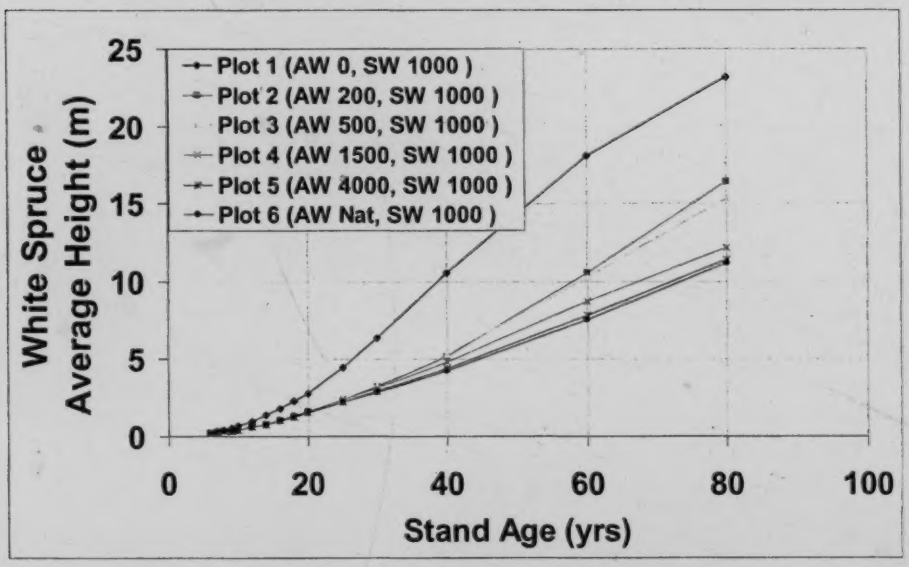

Figure 7.3 Six MGM height growth scenarios with WAHI and RCL models utilized (based on 10cm DBH and 50% of average overstory height as a maximum for understory trees) - legend indicates starting overstory trembling aspen density and understory white spruce density

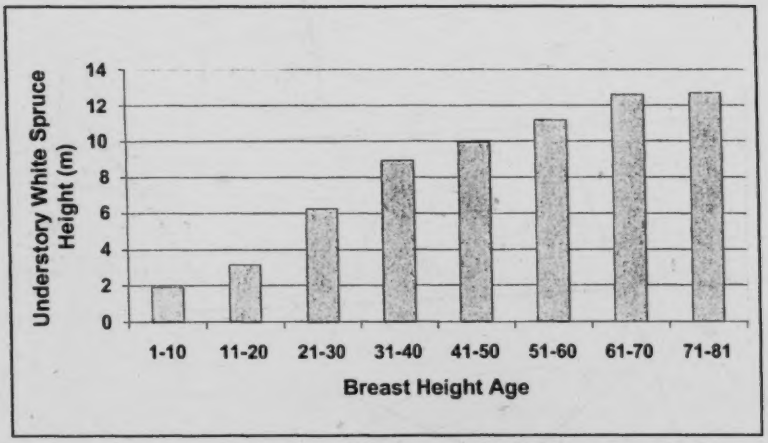

Figure 7.4 Average understory white spruce height by breast height age class – based on project data

7.2 Exploratory assessment of understory white spruce mortality

Tree mortality can be caused by numerous factors including, expected impacts like competition or unpredictable impacts like disease or insect attack. This makes it extremely difficult to develop an accurate mortality model. In this study, mortality data was measured with the goal of performing a preliminary analysis of overstory competition factors impacting the mortality of understory white spruce.

Since field sampling allowed only one visit to plots, the only mortality data collected was an estimation of time since death for every dead understory white spruce found in a plot. Analysis of mortality could only be done at the plot level, as there was insufficient information on the characteristics of the dead trees to use an individual tree approach.

To analyze plot mortality, two potential dependent variables were considered: 1) plot mortality rate per hectare or; 2) proportion of dead understory white spruce (PD). Due to the wide variability of understory white spruce densities between plots, PD was considered a superior variable to mortality rate per hectare. The reason being, that mortality rate per hectare is too closely tied to the number of understory white spruce initially present in a stand and not on trees surviving.

The final dependent variable is:

PD = Count of dead understory spruce / Count of all understory spruce (dead + living)

In an attempt to estimate mortality in a temporal manner, time since death was assessed based on the number of needles that remain attached to the tree. The categories were:

1. Dead less than 2 years – greater than 75% needles still present
2. Dead between 2 and 4 years – between 30% and 75% of needles still present
3. Dead 5+ years – less than 30% of needles present

Upon analysis, it was determined that 97% of all dead understory spruce had less than 30% of the needles present. Only 12 trees of the 427 total dead trees measured (in both regions) retained over 30% of its needles – indicating that virtually all understory white spruce death occurred 5+ years ago. As there is no reason to suspect that mortality on all measured sites effectively ceased 5 years ago, this suggested that this tentative approach of using percentage needle attachment as a method for estimating time of death is unreliable. This coupled with the large number of severely damaged living trees present in the stands (see next section), suggest that death occurs through a process of many years and when it occurs, little foliage remains to be found and drops quickly. As a consequence of this trend, no further analysis that defined death by time was considered desirable.

Another attempt to estimate mortality was based on "dying" understory white spruce. All trees with an overall condition code of severe damage were assumed to be "dying", although it is acknowledged they could remain alive for an indefinite number of years. See Appendix 7.5 for a detailed description of how trees were assigned an overall condition code.

The proportion of severely damaged trees (PSD) was calculated for each plot with the following equation:

PSD = Count of understory spruce severely damaged / Count of all understory spruce (dead + living)

In both regions, the average number of dead understory white spruce per plot was low with a PD of 0.065 for the Boreal sub-region and 0.036 for the Lower Foothills sub-region (Table 7.1,

Table 7.2). Very few plots (in either region) had a PD greater than 0.1 (Figure 7.5, Figure 7.6). For the Boreal sub-region, 101 of a total 150 plots (or 67% of all plots) had a PD of less than 0.01 (or 1%). Similarly in the Lower Foothills sub-region, 50 out of 67 plots (or 75% of all plots) had a PD of less than 0.01. Potential causes for the lower PD in the Lower Foothills sub-region could include: differences in winter snowfall, differences in climate, or perhaps greater wildlife activity in the Lower Foothills sub-region "break down" dead trees sooner (as indicated by 20% of all living understory spruce in the Lower Foothills sub-region having been identified as having some animal damage compared to only 3.9% in the Boreal sub-region), thus reducing the number of dead trees measured.

In both regions, PD did not show a strong relationship with any overstory competition factors (Figure 7.7, Figure 7.9). Although the relationships were weak, similar patterns were evident in both Boreal and Lower Foothills sub-regions. PD had a positive relationship with both overstory crown closure and basal area, suggesting increased overstory competition was associated with understory white spruce mortality. The negative relationship between SF and PD also support this. The results for UCCS, showed that an increased presence of understory competition related to a decrease in understory white spruce mortality. Initially, this appeared counter-intuitive. However, a decrease in overstory competition also resulted in an increase in understory non-tree plant survival and growth. These results may suggest (weakly) that overstory competition is a greater factor in understory white spruce death than competition from understory vegetation.

In both sampling regions, many more severely damaged trees than dead trees were identified. In the Boreal sub-region 23.8% and in the Lower Foothills sub-region 30.3% of all understory white spruce was severely damaged (Table 7.1, Table 7.2). Although the highest frequency of plots had less than 10% severely damaged trees, there were a small but significant number of plots (in both regions) with greater than 50% severely damaged understory white spruce (Figure 7.5, Figure 7.6). This suggests that understory white spruce may be more likely to remain in a state of severe suppression than to die. This is an important point to consider when attempting to model understory spruce because severely damaged trees average significantly less height increment than trees with no damage or minor damage (Table 7.12).

PSD did not strongly relate to any individual overstory competition factors (Figure 7.8, Figure 7.10). However, as with PD there were some weak relationships that were consistent in both the Boreal sub-region and Lower Foothills sub-region. In both regions, plots of overstory crown

closure, basal area, and tree spacing factor all suggested that increased overstory competition resulted in a larger PSD. Understory crown closure at breast height (non-tree species) did not show a clear trend, again suggesting that overstory competition has more of an impact on PSD than competition from understory vegetation.

In conclusion, the analysis shows that there are some trends between understory white spruce death or damage and overstory competition variables. However, the information is not strong enough to allow for development of a predictive model.

Table 7.1 Boreal sub-region – proportion dead understory white spruce per plot

Variable	N	Mean	Standard Error	Variance	Minimum	Maximum	95% Lower Confidence	95% Upper Confidence
Tree Dead for Less Than 2 Years	150	9.53E-04	4.91E-04	3.62E-05	0.000	0.048	-1.76E-05	1.92E-03
Tree Dead for 2 to 4 Years	150	3.03E-03	1.63E-03	3.99E-04	0.000	0.200	-1.88E-04	6.26E-03
Tree Dead for 5+ Years	150	6.13E-02	1.04E-02	1.63E-02	0.000	0.667	4.08E-02	8.19E-02
Severely Damaged	150	0.238	2.03E-02	6.19E-02	0.000	1.000	0.198	0.278

Table 7.2 Lower Foothills sub-region – proportion dead understory spruce per plot

Variable	N	Mean	Standard Error	Variance	Minimum	Maximum	95% Lower Confidence	95% Upper Confidence
Tree Dead for Less Than 2 Years	67	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	.	.
Tree Dead for 2 to 4 Years	67	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	.	.
Tree Dead for 5+ Years	67	3.61E-02	9.65E-03	6.23E-03	0.00	3.48E-01	1.68E-02	5.54E-02
Severely Damaged	67	0.303	3.199E-02	6.858E-02	0.00	1.000	0.239	0.367

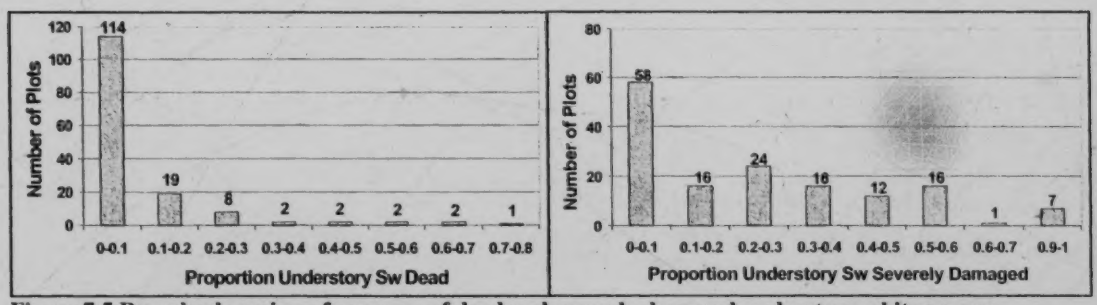

Figure 7.5 Boreal sub-region - frequency of dead and severely damaged understory white spruce (Sw)

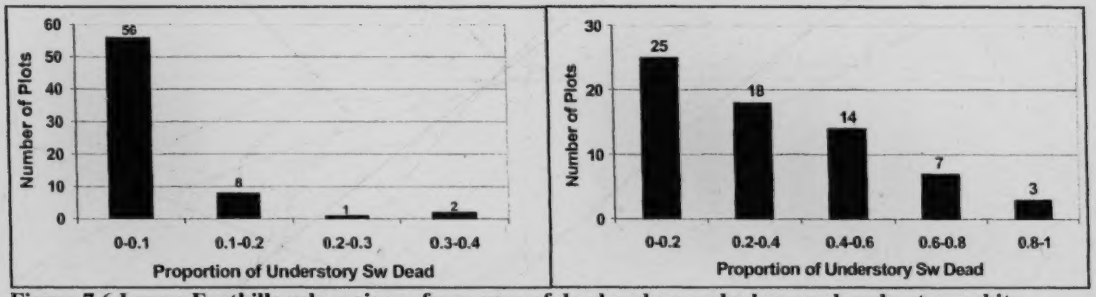

Figure 7.6 Lower Foothills sub-region - frequency of dead and severely damaged understory white spruce (Sw)

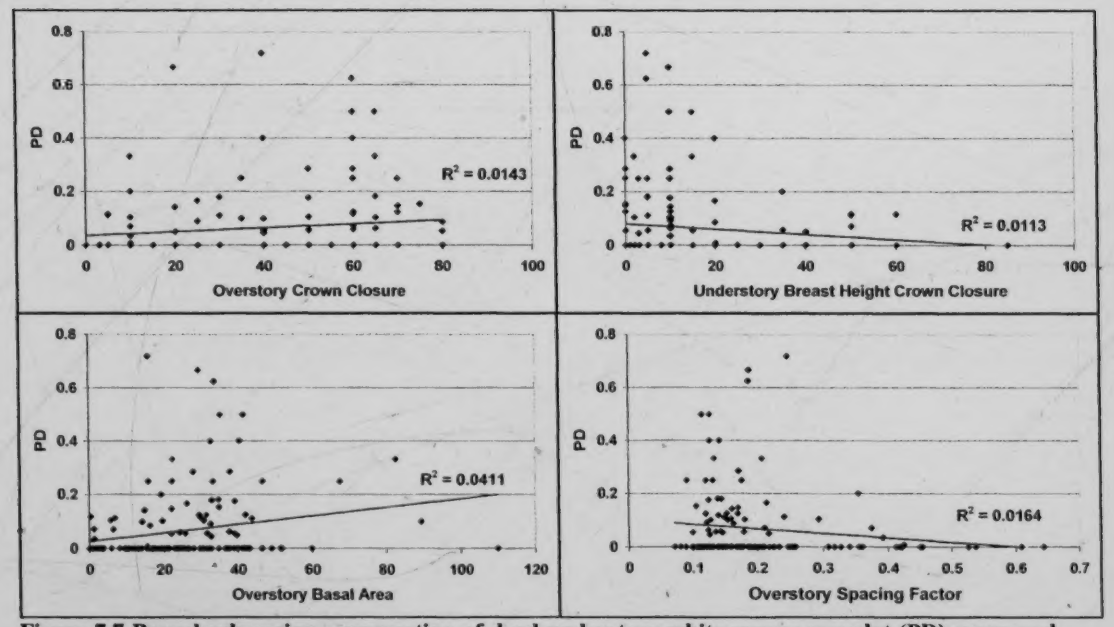

Figure 7.7 Boreal sub-region – proportion of dead understory white spruce per plot (PD) compared to overstory competition variables

Note: All above graphs have the same number of points. Graphs that appear to have fewer points are because some points represent more than one plot.

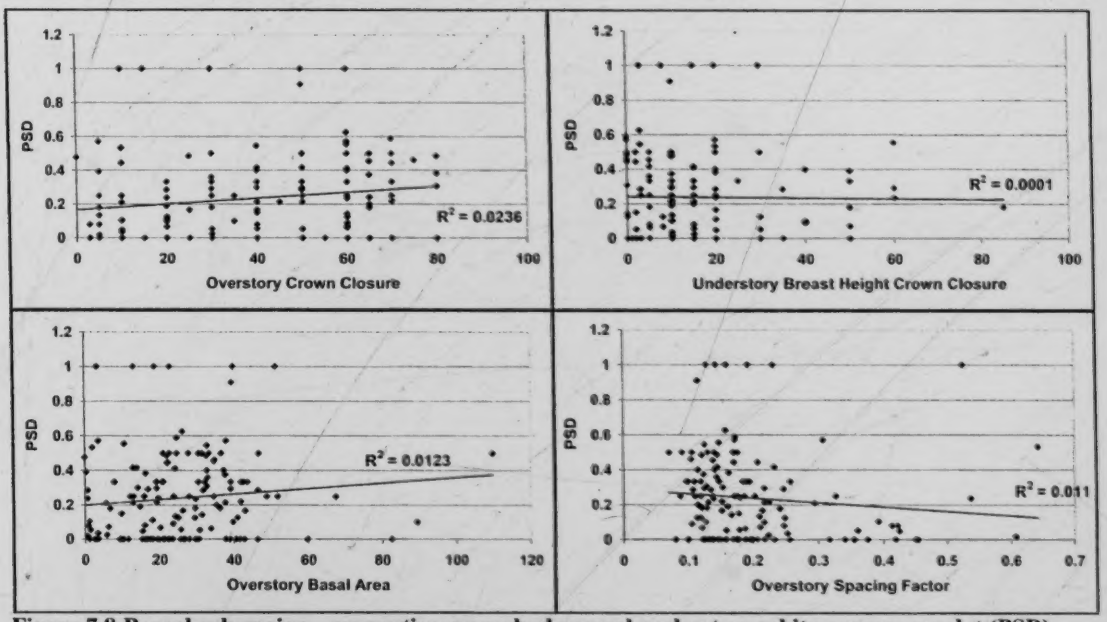

Figure 7.8 Boreal sub-region - proportion severely damaged understory white spruce per plot (PSD) compared to overstory competition variables

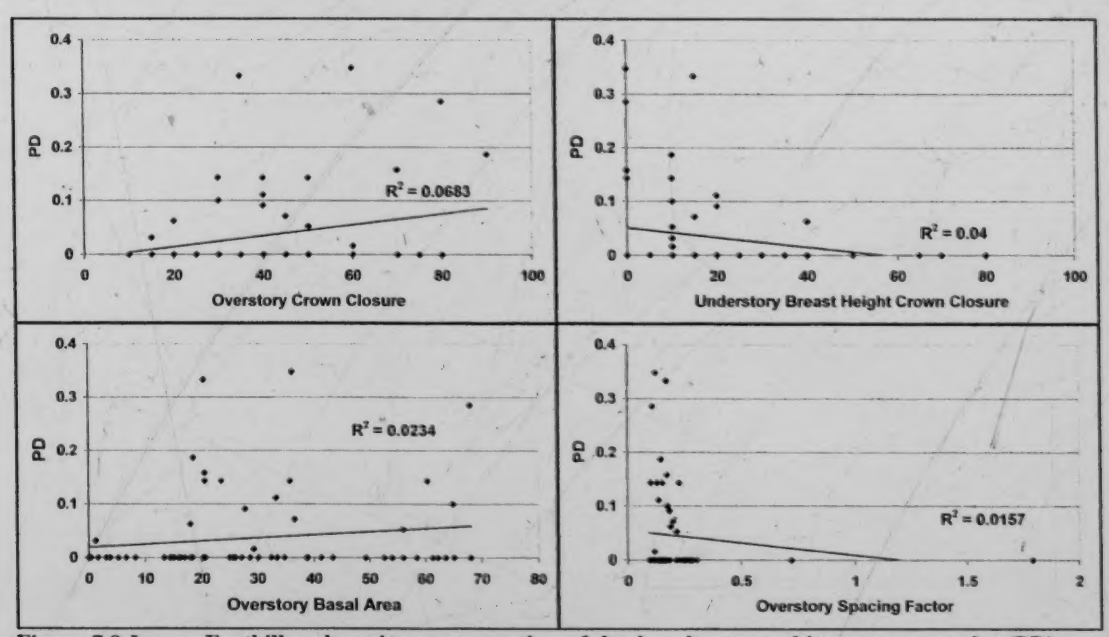

Figure 7.9 Lower Foothills sub-region – proportion of dead understory white spruce per plot (PD) compared to overstory competition variables

Note: All above graphs have the same number of points. Graphs that appear to have fewer points are because some points represent more than one plot.

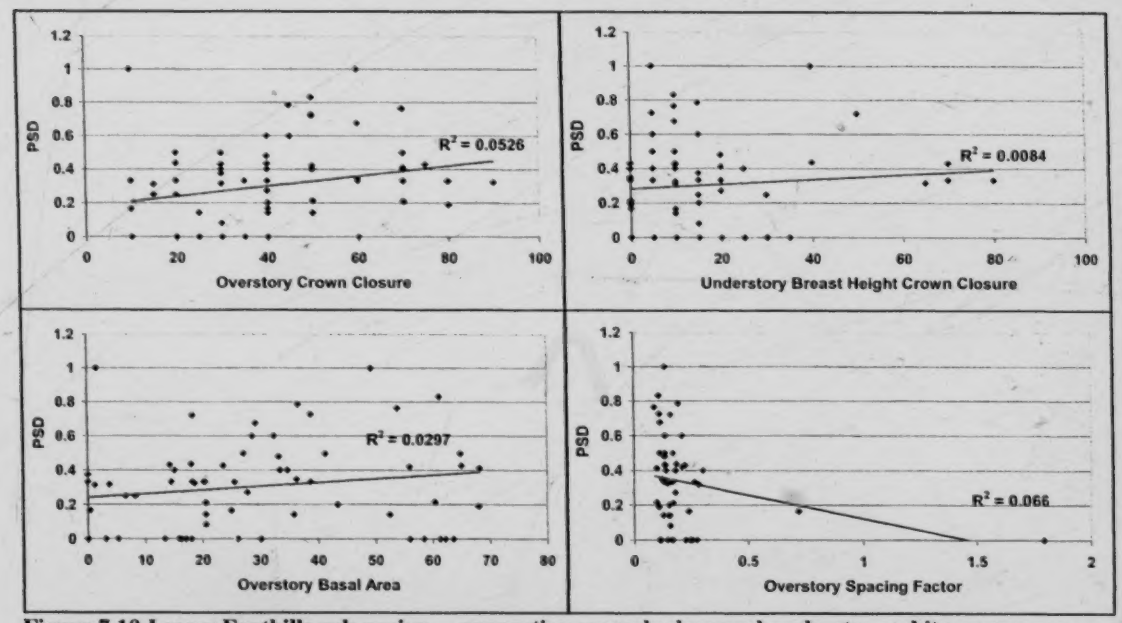

Figure 7.10 Lower Foothills sub-region - proportion severely damaged understory white spruce per plot (PSD) compared to overstory competition variables

7.3 Relationship between breast age, breast height diameter, understory white spruce density, and overstory tree spacing factor

The relationship between breast age, DBH, understory spruce density (USWD) and overstory tree spacing factor were examined for both sub-regions (Figure 7.11, Figure 7.12). To summarize the results:

1. A strong linear relationship between DBH and Bage was observed.
2. As understory spruce DBH and Bage increase there is a general trend of decreased USWD. This decrease is more dramatic in the Boreal sub-region than in the Lower Foothills sub-region.
3. There is a difference between sub-regions with the relationship between SF and understory spruce DBH (and Bage). In the boreal forest higher DBH (and Bage) is associated with lower SF; where as in the lower foothills there is no relationship.

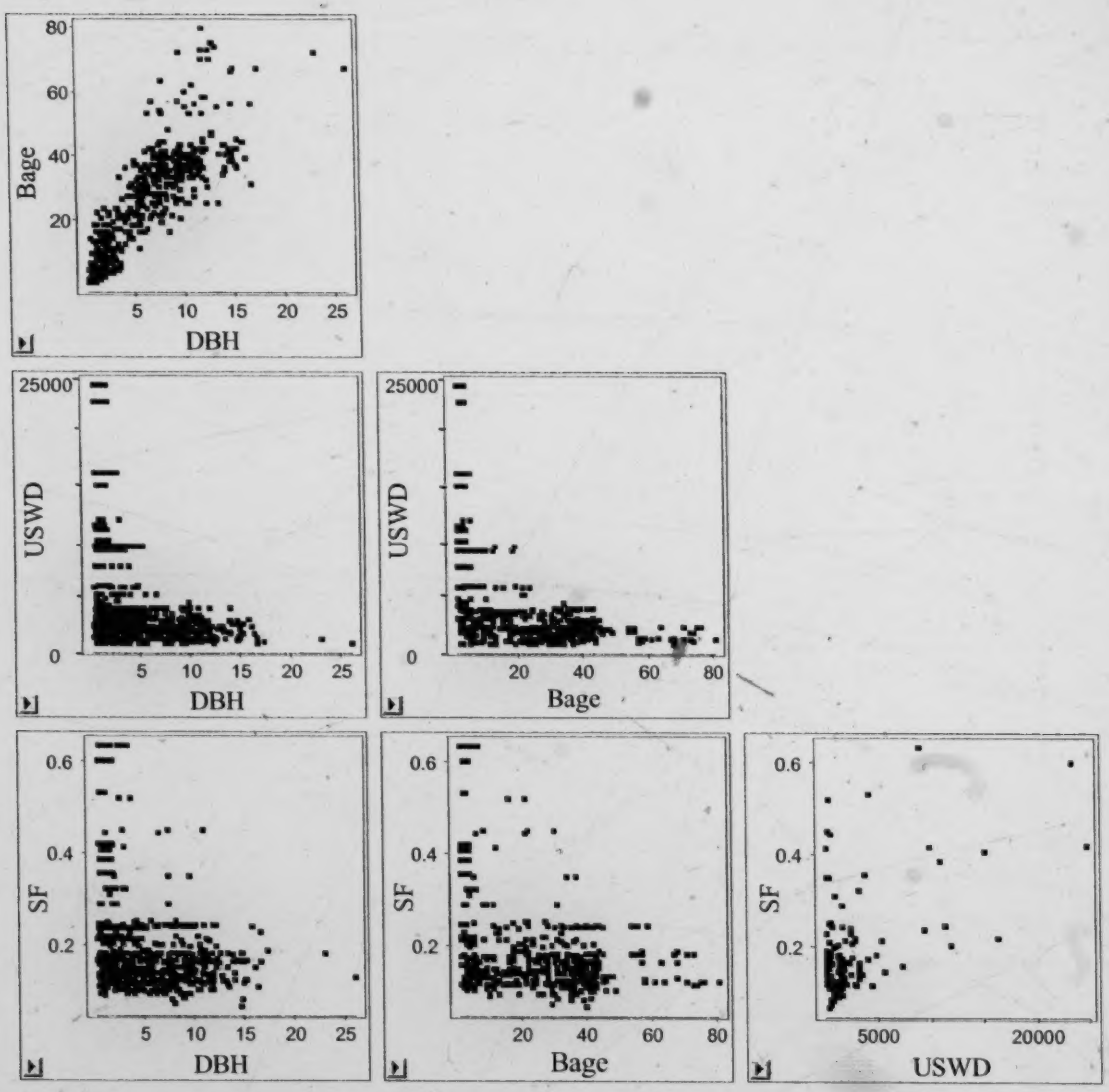

Figure 7.11 Boreal sub-region - plot matrix of understory spruce breast height age (Bage), understory spruce breast height diameter (DBH), overstory tree spacing factor (SF), and understory white spruce density (USWD)

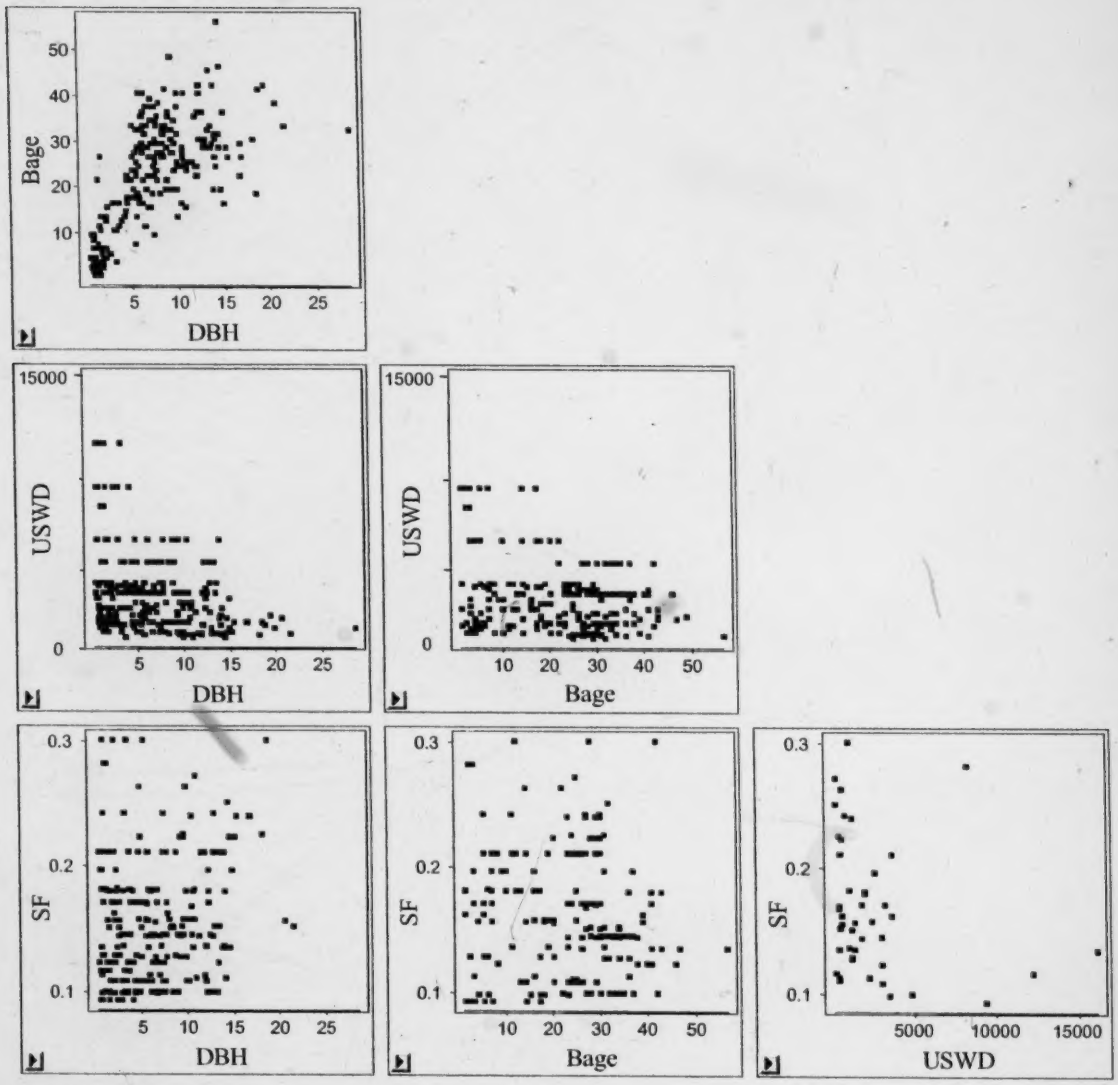

Figure 7.12 Lower Foothills sub-region - plot matrix of understory spruce breast height age (Bage), understory spruce breast height diameter (DBH), overstory tree spacing factor (SF), and understory white spruce density (USWD)

7.4 Measuring diffuse non-interceptance

When possible a measurement of diffuse non-interceptance (DIFN) was taken at each plot centre. DIFN is an estimate of the amount of sky not blocked by foliage, thus giving a proportion of light transmitted. DIFN was estimated by using LAI-2000 plant canopy analyzer, which concurrently estimates the amount of solar radiation at five zenith angles (those angles being: 0-13°, 16-28°, 32-43°, 47-58°, 61-74°). Two LAI-2000 units were used to simultaneously estimate radiation levels above and below the vegetative canopy. This was done by placing one unit in an open area (as close to the sampling area as possible) and setting it to automatically take a reading every 30 seconds. Meanwhile, readings were taken at plot centre. The proportional difference between the open and below canopy reading was calculated for each of the five angles. The following equation was used to estimate DIFN (LI-COR, 1992):

$$DIFN = PA1 \cdot 0.066 + PA2 \cdot 0.189 + PA3 \cdot 0.247 + PA4 \cdot 0.249 + PA5 \cdot 0.249$$

DIFN – Diffuse Non-Interceptance
PA1 – Proportion of radiation transmitted to below canopy reading from angle 1 (0-13°)
PA2 – Proportion of radiation transmitted to below canopy reading from angle 2 (16-28°)
PA3 – Proportion of radiation transmitted to below canopy reading from angle 3 (32-43°)
PA4 – Proportion of radiation transmitted to below canopy reading from angle 4 (47-58°)
PA5 – Proportion of radiation transmitted to below canopy reading from angle 5 (61-74°)

Below canopy readings were taken at the estimated average mid-point of the live crown of understory white spruce (to a maximum height of 4m). For example if the plot average understory white spruce was 3m tall with a 1m height to live crown (making a 2m live crown); the measurement was taken at 2m (1m height to live crown + ½ x 2m – live crown = 2m).

7.5 Understory white spruce codes and overall assumed damage level

All living understory spruce were assigned three condition codes that described bole, leader, and canopy characteristics. To simplify analysis of understory spruce damage, the three tree condition codes (bole, leader, and canopy) were combined into a single overall damage code. This code was produced based on the following decision rules and Table 7.3:

1. A tree with a severe damage bole code was considered to have overall code of severe damage.

2. A tree assigned only one minor damage condition code and two no damage codes was considered to have overall minor damage.
3. A tree assigned three no damage condition codes was considered to overall have no damage.
4. A tree assigned two or more minor damage condition codes was considered to have overall severe damage.

Table 7.3 Bole, leader, and canopy conditions codes and assumed damage level

Bole Codes		
Condition Code	**Full Title**	**Assumed Damage Level**
X1	Standing Dead Condition 1	Dead
X2	Standing Dead Condition 2	Dead
X3	Standing Dead Condition 3	Dead
D1	Dead & Down Condition 1	Dead
D2	Dead & Down Condition 2	Dead
D3	Down & Down Condition 3	Dead
CD	Cut Down	Dead
BS	Broken / Missing Stem	Severe Damage
HL	Heavy Lean	Severe Damage
GI	Girdled	Severe Damage
RD	Root Damage	Severe Damage
SG	Stem Galls/Burls	Severe Damage
CK	Crook / Sweep	Minor Damage
FK	Fork	Minor Damage
SL	Slight Lean	Minor Damage
OS	Open Scar	Minor Damage
FH	Frost Heave	Minor Damage
CS	Closed Scar	Minor Damage
CO	Conks	Minor Damage
OK	No Defect	No Damage

Leader Codes		
Condition Code	**Full Title**	**Assumed Damage Level**
BT	Broken / Missing Leader	Minor Damage
DT	Dead Leader / Leader Die Back	Minor Damage
NL	New Leader	Minor Damage
ML	Multiple Leader	Minor Damage
OK	No Defect	No Damage

Canopy Codes		
Condition Code	**Full Title**	**Assumed Damage Level**
SL	Severe Leaf Loss	Minor Damage
ML	Moderate Leaf Loss	Minor Damage
BG	Branch Galls/Burls	Minor Damage
MT	Mistletoe	Minor Damage
WB	Witches Broom	Minor Damage
PV	Poor Vigor	Minor Damage
OK	No Defect	No Damage

7.6 Plot Summary characteristics

In the Boreal forest sub-region, a total of 159 plots were sampled; whereas in the Lower Foothills sub-region a total of 69 plots (plus 3 removed for not being typical) were sampled. In both regions, the overstory was predominately deciduous. In the Boreal sub-region, there was an average of 1896 deciduous stems/ha compared to 261 overstory coniferous stems per ha (Table 7.4). Similarly in the Lower Foothills sub-region, there was an average of 1324 deciduous stems/ha compared to 87 overstory coniferous stems per ha (Table 7.5).

In both regions the overstory competition levels varied widely, from plots with a high density of 22,800 stems/ha and 9,800 stems/ha in the Boreal and Lower Foothills sub-regions respectively,

to plots with no overstory stems present. Stand overstory basal area also varied widely from 0 m^2/ha to 110 m^2/ha in the Boreal sub-region and 0 m^2/ha to 89 m^2/ha in the Lower Foothills sub-region.

In the Boreal sub-region, the understory tree species was predominately white spruce. The density of understory white spruce was 2,142 stems/ha, were as the average density of all other understory species combined was 1,249 stems/ha. This predominance of white spruce in the understory was greater in the Lower Foothills sub-region with an average white spruce density of 1,839 stems/ha compared to the average density of all other understory species combined of 554 stems/ha.

The plot statistics for both overstory and understory indicated that the goal of sampling across the range of variability was obtained. The widely varying stand types had both positive and negative implications for the study. Positively, there was an opportunity to understand in general terms the trends occurring across a wide range of stand types. Negatively, the number of variables and the variance greatly increased, making it more difficult to evaluate observed trends.

Table 7.4 Boreal sub-region - summary of plot variables

Variable	N	Mean	Standard Error	Variance	Minimum	Maximum	Lower 95% CL	Upper 95% CL
Overstory Crown Closure	159	41.36	1.75	484.78	0	80	37.91	44.81
Understory Crown Closure at Stump Height	159	43.37	2.15	733.70	0	90	39.13	47.61
Understory Crown Closure at Breast Height	159	13.53	1.15	209.93	0	85	11.27	15.80
Total Crown Closure	159	84.73	2.35	877.87	15	155	80.09	89.37
Overstory Deciduous Density per ha	159	1,896.23	220.45	7,727,327.44	0	22,800	1,460.81	2,331.64
Overstory Coniferous Density per ha	159	261.64	39.06	242,632.75	0	2,800	184.48	338.79
Overstory Density per ha (Deciduous and Coniferous)	159	2,157.86	223.06	7,911,314.39	0	22,800	1,717.29	2,598.43
Overstory Dead Trees per ha	159	503.77	61.01	591,884.40	0	5,400	383.27	624.28
Overstory Basal Area per ha (Coniferous and Deciduous)	159	25.21	1.35	289.53	0	110	22.54	27.87
Overstory Coniferous Basal Area per ha	159	4.92	0.63	62.50	0	34	3.68	6.15
Overstory Deciduous Basal Area per ha	159	20.29	1.39	305.16	0	110	17.56	23.03
Overstory Tree Spacing Factor (Coniferous and Deciduous)*	151	0.195	0.008	0.010	0.07078	0.643	0.179	0.212
Overstory Coniferous Tree Spacing Factor*	151	0.707	0.027	0.109	0.12515	1.000	0.654	0.760
Overstory Deciduous Tree Spacing Factor*	151	0.236	0.013	0.026	0.07078	1.000	0.211	0.262
Understory White Spruce Density per ha	159	2,142.77	294.67	13,806,260.65	0	25,000	1,560.76	2,724.77
Understory Non-White Spruce Species Density per ha	159	1,249.06	189.69	5,721,375.69	0	18,000	874.40	1,623.72
Understory Density per ha (includes all species)	159	3,391.82	377.55	22,664,299.82	0	26,200	2,646.13	4,137.52
Understory Dead Trees per ha	159	308.81	55.86	496,124.51	0	7,000	198.48	419.13

* Tree Spacing Factor Values were not possible on 8 plots.

Table 7.5 Lower Foothills sub-region - summary of plot variables

Variable	N	Mean	Standard Error	Variance	Minimum	Maximum	Lower 95% CL	Upper 95% CL
Overstory Crown Closure	69	40.14	2.33	376.45.	10	80	35.48	44.81
Understory Crown Closure at Stump Height	69	55.14	3.43	813.95	5	100	48.29	62.00
Understory Crown Closure at Breast Height	69	16.09	2.14	316.82	0	80	11.81	20.36
Total Crown Closure	69	95.29	2.35	383.003	55	135	90.59	99.99
Overstory Deciduous Density per ha	69	1,324.64	178.60	2,201,001.71	0	9,800	968.24	1,681.03
Overstory Coniferous Density per ha	69	86.96	25.19	43,797.95	0	1,400	36.68	137.23
Overstory Density per ha (Deciduous and Coniferous)	69	1,411.59	178.66	2,202,510.66	0	9,800	1,055.08	1,768.11
Overstory Dead Trees per ha	69	281.16	53.05	194,198.64	0	3,200	175.30	387.02
Overstory Basal Area per ha (Coniferous and Deciduous)	69	29.27	2.66	489.77	0	89	23.95	34.59
Overstory Coniferous Basal Area per ha	69	3.88	1.13	88.58	0	57	1.62	6.14
Overstory Deciduous Basal Area per ha	69	25.39	2.57	457.05	0	89	20.25	30.53
Overstory Tree Spacing Factor (Coniferous and Deciduous)*	54	0.208	0.032	0.056	0.09393	1.791	0.143	0.272
Overstory Coniferous Tree Spacing Factor*	54	0.830	0.040	0.084	0.18553	1.000	0.751	0.910
Overstory Deciduous Tree Spacing Factor*	54	0.216	0.032	0.056	0.09393	1.791	0.152	0.281
Understory White Spruce Density per ha	69	1839.13	336.66	7,820,652.17	0	16,200	1,167.33	2,510.93
Understory Non-White Spruce Species Density per ha	69	553.62	164.14	1,858,994.03	0	10,400	226.09	881.15
Understory Density per ha (includes all species)	69	2,392.75	457.06	14,414,505.54	0	26,600	1,480.70	3,304.81
Understory Dead Trees per ha	69	140.58	53.05	19,421.42	0	2,800	34.71	246.45

* Tree Spacing Factor Values were not possible on 15 plots.

7.7 Individual overstory tree characteristics

In the Boreal sub-region, a total of 2310 live overstory trees were sampled (2917 including standing dead trees); and in the Lower Foothills sub-region a total of 648 live overstory trees were sampled (754 including stand dead trees). In both sampling regions, trembling aspen was the most frequently measured overstory tree species (Table 7.6, Table 7.7). The mean height of trembling aspen was approximately 16.25m for both sampling regions. Mean breast height age was also very similar for both regions at almost 50 years. These summary statistics show that the overstory of sampled stands had a large deciduous component (especially trembling aspen) with a wide range of heights and ages.

Table 7.6 Boreal sub-region – summary of sampled individual overstory trees

Sp	Number Sampled	Variable	Mean	Standard Error	Variance	Minimum	Maximum	Lower 95% CL	Upper 95% CL
AW	338	Height	16.2	0.34	38.72	2.56	28.30	15.48	16.82
	338	Height to Live Crown	10.3	0.26	22.62	0.46	22.19	9.80	10.82
	1471	DBH	10.6	0.20	60.02	0.44	43.40	10.19	10.98
	240	Age at Breast Height	49.6	1.46	514.86	9.00	98.00	46.67	52.44
BW	2	Height	9.1	0.73	1.05	8.37	9.82	-0.12	18.31
	2	Height to Live Crown	1.6	0.00	0.00	1.60	1.60	.	.
	272	DBH	6.3	0.31	26.33	0.40	51.90	5.72	6.95
	1	Age at Breast Height	20.0	.	.	20.00	20.00	.	.
PB	1	Height	14.7	.	.	14.70	14.70	.	.
	1	Height to Live Crown	12.2	.	.	12.20	12.20	.	.
	243	DBH	8.0	0.42	42.65	0.65	32.90	7.17	8.82
	1	Age at Breast Height	57.0	.	.	57.00	57.00	.	.
FB	0	Height	N/A	.	.	.	.	.	.
	0	Height to Live Crown	N/A	.	.	.	.	.	.
	26	DBH	8.2	0.95	23.37	2.88	25.00	6.27	10.17
	0	Age at Breast Height	N/A	.	.	.	.	.	.
PJ	0	Height	N/A	.	.	.	.	.	.
	0	Height to Live Crown	N/A	.	.	.	.	.	.
	73	DBH	13.4	0.79	45.22	5.20	44.90	11.82	14.96
	0	Age at Breast Height	N/A	.	.	.	.	.	.
SB	1	Height	14.1	.	.	14.12	14.12	.	.
	1	Height to Live Crown	6.8	.	.	6.77	6.77	.	.
	79	DBH	13.5	0.40	12.78	5.10	27.80	12.73	14.33
	1	Age at Breast Height	58.0	.	.	58.00	58.00	.	.
SW	111	Height	13.7	0.35	13.88	4.08	24.80	13.04	14.44
	118	Height to Live Crown	5.6	0.25	7.51	0.17	15.72	5.14	6.13
	139	DBH	16.1	0.51	36.49	5.00	45.20	15.06	17.08
	91	Age at Breast Height	43.8	1.59	230.58	18.00	92.00	40.67	46.99

Table 7.7 Lower Foothills sub-region - summary of sampled individual overstory trees

Sp	Number Sampled	Variable	Mean	Standard Error	Variance	Minimum	Maximum	Lower 95% CL	Upper 95% CL
AW	105	Height	15.8	0.725	55.218	1.29	31.5	14.408	17.284
	104	Height to Live Crown	9.8	0.544	30.730	0.38	22.4	8.689	10.845
	256	DBH	13.3	0.663	112.437	0.35	61.0	11.990	14.600
	79	Age at Breast Height	43.7	3.290	855.081	1.00	125.0	37.159	50.259
BW	4	Height	11.2	1.514	9.168	7.6	14.8	6.397	16.033
	4	Height to Live Crown	4.9	1.407	7.919	2.79	9.03	0.397	9.353
	110	DBH	6.9	0.431	20.465	0.7	29	6.035	7.745
	2	Age at Breast Height	40.5	23.5	1104.5	17	64	-258.096	339.096
PB	55	Height	16.0	0.726	29.019	5.24	27.8	14.545	17.457
	54	Height to Live Crown	9.4	0.569	17.456	2.14	19.5	8.285	10.566
	128	DBH	13.6	0.899	103.397	0.8	56.2	11.851	15.409
	37	Age at Breast Height	46.4	3.123	360.964	14	92	40.044	52.713
FB	0	Height	N/A	.	.	.	.	.	.
	0	Height to Live Crown	N/A	.	.	.	.	.	.
	4	DBH	12.4	2.424	23.5	8	19.3	4.686	20.114
	0	Age at Breast Height	N/A	.	.	.	.	.	.
PL	1	Height	15.4	.	.	15.4	15.4	.	.
	0	Height to Live Crown	N/A	.	.	.	.	.	.
	1	DBH	13.5	.	.	13.5	13.5	.	.
	0	Age at Breast Height	N/A	.	.	.	.	.	.
SB	2	Height	13.47	0.14	0.0392	13.33	13.61	11.691	15.249
	2	Height to Live Crown	3.58	0.14	0.0392	3.44	3.72	1.801	5.359
	2	DBH	17.45	1.050	2.205	16.4	18.5	4.108	30.792
	0	Age at Breast Height	N/A	.	.	.	.	.	.
SW	25	Height	16.3	0.976	23.827	9.36	26.3	14.271	18.301
	25	Height to Live Crown	5.2	0.588	8.656	1.81	11.8	3.945	6.374
	26	DBH	23.4	2.011	105.188	9	48.7	19.250	27.535
	22	Age at Breast Height	47.0	5.347	629.093	17	102	35.834	58.075

7.7.1 Understory spruce trees characteristics

Table 7.8 Boreal sub-region - summary statistics of individual understory white spruce greater than 1.3m in height

Variable	N	Mean	Standard Error	Variance	Minimum	Maximum	Lower 95% CL for Mean	Upper 95% CL for Mean
Total Height	859	4.992	0.120	12.318	1.32	16.50	4.757	5.227
Height to Live Crown	855	2.276	0.070	4.147	0.14	9.80	2.140	2.413
Crown Length	855	2.719	0.069	4.019	0.01	12.90	2.584	2.853
Relative Crown Length	855	0.578	0.006	0.035	0.00	0.97	0.566	0.591
Root Collar Diameter	7	2.849	0.781	4.269	0.78	6.87	0.938	4.760
Diameter at Breast Height	865	4.679	0.137	16.171	0.26	26.30	4.410	4.947
Stump Height Age	318	28.824	0.787	197.054	7.00	87.00	27.275	30.373
Breast Height Age	636	22.049	0.696	307.804	1.00	81.00	20.683	23.415
AAHI	535	13.776	0.374	74.782	0.17	42.50	13.042	14.511
WAHI	535	0.084	0.002	0.003	0.00	0.24	0.080	0.089

Table 7.9 Lower Foothills sub-region - summary statistics of individual understory white spruce greater than 1.3m in height

Variable	N	Mean	Standard Error	Variance	Minimum	Maximum	Lower 95% CL for Mean	Upper 95% CL for Mean
Total Height	304	5.772	0.202	12.351	1.31	17.23	5.375	6.168
Height to Live Crown	304	2.185	0.087	2.307	0.23	8.50	2.013	2.356
Crown Length	304	3.587	0.153	7.109	0.18	13.44	3.286	3.888
Relative Crown Length	304	0.598	0.010	0.032	0.04	0.91	0.578	0.618
Root Collar Diameter	26	2.220	0.176	0.806	1.40	5.95	1.858	2.583
Diameter at Breast Height	296	6.542	0.279	23.012	0.30	28.80	5.994	7.091
Stump Height Age	208	27.591	0.767	122.252	2.00	61.00	26.080	29.103
Breast Height Age	233	22.639	0.793	146.369	1.00	57.00	21.078	24.201
AAHI	195	17.864	0.931	169.012	2.00	70.33	16.028	19.700
WAHI	193	0.086	0.004	0.003	0.01	0.24	0.079	0.093

Table 7.10 Boreal sub-region - summary statistics of individual understory white spruce less than 1.3m in height

Variable	N	Mean	Standard Error	Variance	Minimum	Maximum	Lower 95% CL for Mean	Upper 95% CL for Mean
Total Height	1207	0.506	0.010	0.112	0.03	1.30	0.487	0.525
Height to Live Crown	1126	0.261	0.005	0.028	0.02	0.99	0.251	0.271
Crown Length	1126	0.261	0.007	0.053	0.01	1.12	0.247	0.274
Relative Crown Length	1126	0.438	0.006	0.036	0.03	0.91	0.427	0.449
Root Collar Diameter	1127	0.776	0.020	0.450	0.01	8.35	0.737	0.815
Diameter at Breast Height	N/A	.	.	.	.	.	.	.
Stump Height Age	1119	6.829	0.124	17.321	1.00	31.00	6.585	7.073
Breast Height Age	N/A	.	.	.	.	.	.	.
AAHI	1111	4.476	0.086	8.203	0.03	30.00	4.307	4.645
WAHI	1111	0.065	0.001	0.001	0.00	0.32	0.063	0.066

Table 7.11 Lower Foothills sub-region - summary statistics of individual understory white spruce less than 1.3m in height

Variable	N	Mean	Standard Error	Variance	Minimum	Maximum	Lower 95% CL for Mean	Upper 95% CL for Mean
Total Height	347	0.503	0.015	0.083	0.05	1.30	0.472	0.533
Height to Live Crown	327	0.215	0.009	0.026	0.01	1.05	0.197	0.232
Crown Length	327	0.300	0.012	0.043	0.00	1.05	0.278	0.323
Relative Crown Length	327	0.575	0.010	0.033	0.00	0.94	0.555	0.595
Root Collar Diameter	347	0.730	0.026	0.232	0.04	2.96	0.679	0.780
Diameter at Breast Height	N/A	.	.	.	.	.	.	.
Stump Height Age	217	5.963	0.341	25.165	1.00	28.00	5.292	6.634
Breast Height Age	N/A	.	.	.	.	.	.	.
AAHI	292	5.755	0.236	16.289	0.33	28.00	5.290	6.219
WAHI	292	0.079	0.002	0.002	0.00	0.25	0.075	0.084

7.7.2 Height increment and qualitative variables

Each sampled understory white spruce was assigned values describing the qualitative characteristics of the tree. This section examines the potential differences in height increment associated with different qualitative variables. The four data sets examined are:

1. Boreal sub-region – Understory White Spruce Greater than 1.3m in Height (Table 7.12)
2. Boreal sub-region - Understory White Spruce Less than 1.3m in Height (Table 7.13)
3. Lower Foothills sub-region – Understory White Spruce Greater than 1.3m in Height (Table 7.14)
4. Lower Foothills sub-region - Understory White Spruce Less than 1.3m in Height (Table 7.15)

Results suggested a substantial difference in average height increment between natural and planted understory white spruce. In the Boreal sub-region, planted understory white spruce greater than 1.3m in height averaged 8cm greater AAHI than natural understory white spruce (Table 7.12). This difference was also present in juvenile Boreal sub-region spruce with planted trees averaging 4cm greater AAHI over naturally occurring spruce (Table 7.13). In the Lower Foothills sub-region this difference in juvenile understory white spruce was even larger with an average greater growth of 10cm of planted spruce over natural (Table 7.15). Planted trees were identified from traces of scarification, suggesting increased average height increment from silvicultural treatments (Landhausser et al. 2000, Groot 1999) rather than improved growth from planting in-and-of itself.

In both sub-regions, intermediate understory white spruce showed significantly higher AAHI than suppressed white spruce. In the Boreal sub-region, intermediate understory white spruce greater than 1.3m in height show an AAHI of 17cm, compared to suppressed trees with an AAHI of 12cm. Juvenile intermediate understory white spruce also showed improved AAHI over suppressed juveniles (1cm), however it was not significant at 95% confidence. In the Lower Foothills sub-region, this trend increased with intermediate understory white spruce showing an increased AAHI of 16cm over suppressed trees. This trend also occurred with juvenile understory white spruce (intermediate spruce show an increased AAHI of 13cm over suppressed – significant at 95% confidence).

The results indicated that in both regions (both juveniles and trees greater than 1.3m in height), severely damaged understory white spruce put on significantly less height increment than trees that had experienced minor or no damage. This difference appeared highest in the Lower Foothills sub-region with minor damaged and no damaged white spruce, showing greater than 10cm improved height increment over severely damaged trees (Table 7.14). This difference also occurred in the Boreal sub-region with severely damaged white spruce, averaging 6 cm less height increment per year (Table 7.12).

The relationship between AAHI and ecosite was somewhat complex, representing a wide range of nutrient and moisture regimes. The moisture regimes ranged from near subxeric to near subhydric, while the nutrient regimes ranged from bordering on poor nutrient regime to bordering on very rich. In general, dryer sites have lower nutrient levels than wetter sites, suggesting some type of balance between nutrients and moisture was required.

Understory white spruce AAHI showed some significant difference between ecosites. However, the number of potential factors differing between ecosites was large and this study only allowed for a preliminary analysis.

Table 7.12 Boreal sub-region – average annual height increment of understory white spruce greater than 1.3m in height - classified by qualitative explanatory variables

Variable	N	Mean AAHI	Standard Error	Variance	Minimum AAHI	Maximum AAHI	Lower 95% CL for Mean	Upper 95% CL for Mean
Planted or Natural								
Natural	382	11.6572	0.4305	70.8003	0.17	42.50	10.8107	12.5037
Planted	153	19.0664	0.5471	45.7997	2.83	40.67	17.9855	20.1474
Crown Class								
Intermediate	142	17.2313	0.8498	102.5399	0.17	42.50	15.5513	18.9112
Suppressed	393	12.5277	0.3878	59.1013	0.23	40.67	11.7652	13.2901
Tree Codes								
No Damage	166	15.5522	0.6830	77.4385	1.83	40.67	14.2036	16.9007
Minor Damage	202	15.8240	0.5930	71.0325	0.17	42.50	14.6547	16.9933
Severe Damage	167	9.5335	0.5538	51.2170	0.23	31.33	8.4401	10.6269
Ecosite								
B1	44	7.6539	0.7227	22.9807	1.67	22.33	6.1964	9.1113
B2	4	14.1750	3.2296	41.7225	7.80	23.10	3.8968	24.4532
B3	2	4.1150	0.7150	1.0225	3.40	4.83	-4.9699	13.1999
D1	220	15.0447	0.5426	64.7725	1.67	42.50	13.9753	16.1141
D2	205	13.8640	0.6375	83.3082	0.17	40.67	12.6071	15.1209
E1	23	19.0461	1.3633	42.7465	10.00	33.00	16.2188	21.8734
E2	35	9.6806	1.6013	89.7420	1.33	40.10	6.4264	12.9347
F1	2	19.8350	8.8350	156.1145	11.00	28.67	-92.4243	132.0943

Table 7.13 Boreal sub-region – average annual height increment of understory white spruce less than 1.3m in height (Juveniles) - classified by qualitative explanatory variables

Variable	N	Mean AAHI	Standard Error	Variance	Minimum AAHI	Maximum AAHI	Lower 95% CL for Mean	Upper 95% CL for Mean
Planted or Natural								
Natural	1034	4.2653	0.0835	7.2007	0.03	30.00	4.1015	4.4291
Planted	77	7.3058	0.4144	13.2214	0.67	17.93	6.4805	8.1311
Crown Class								
Intermediate	4	5.4500	0.3706	0.5493	4.77	6.43	4.2707	6.6293
Suppressed	1107	4.4725	0.0862	8.2280	0.03	30.00	4.3034	4.6417
Tree Codes								
No Damage	482	4.6530	0.1411	9.5947	0.27	30.00	4.3758	4.9303
Minor Damage	379	4.7275	0.1451	7.9785	0.03	17.93	4.4423	5.0128
Severe Damage	250	3.7534	0.1448	5.2415	0.07	13.43	3.4683	4.0386
Ecosite								
B1	46	3.0150	0.2234	2.2958	0.03	9.13	2.5650	3.4650
B2	6	2.7717	0.5463	1.7908	1.40	4.60	1.3673	4.1760
B3	5	2.8200	0.6660	2.2175	0.93	5.10	0.9710	4.6690
D1	718	4.4696	0.1111	8.8624	0.27	30.00	4.2514	4.6877
D2	253	4.3215	0.1549	6.0721	0.07	14.33	4.0164	4.6266
E1	72	6.2182	0.3567	9.1617	1.77	16.00	5.5069	6.9295
E2	6	5.0167	1.7138	17.6228	1.47	12.57	0.6112	9.4221
F1	5	4.6340	0.5285	1.3967	3.67	6.67	3.1666	6.1014

Table 7.14 Lower Foothills sub-region – average annual height increment of understory white spruce greater than 1.3m in height - classified by qualitative explanatory variables

Variable	N	Mean AAHI	Standard Error	Variance	Minimum AAHI	Maximum AAHI	Lower 95% CL for Mean	Upper 95% CL for Mean
Planted or Natural								
Natural	195	17.8643	0.9310	169.0120	2.00	70.33	16.0281	19.7004
Planted	N/A							
Crown Class								
Intermediate	65	28.8751	1.7476	198.5205	3.57	70.33	25.3838	32.3663
Suppressed	130	12.3588	0.7019	64.0489	2.00	41.67	10.9701	13.7476
Tree Codes								
No Damage	72	24.4988	1.7749	226.8187	3.33	70.33	20.9597	28.0378
Minor Damage	64	19.3641	1.1626	86.5115	3.00	51.33	17.0407	21.6874
Severe Damage	59	8.1410	0.8274	40.3946	2.00	32.00	6.4847	9.7973
Ecosite								
E2	2	17.1700	4.5000	40.5000	12.67	21.67	-40.0079	74.3479
E3	52	13.9487	1.8517	178.2922	2.00	70.33	10.2313	17.6660
F2	77	19.8339	1.3654	143.5479	2.33	50.67	17.1145	22.5533
F3	53	20.1945	1.9686	205.4031	2.67	57.33	16.2442	24.1449
I1	11	11.4855	1.4523	23.2001	4.00	19.00	8.2496	14.7213

Table 7.15 Lower Foothills sub-region – average annual height increment of understory white spruce less than 1.3m in height (juveniles) - classified by qualitative explanatory variables

Variable	N	Mean AAHI	Standard Error	Variance	Minimum AAHI	Maximum AAHI	Lower 95% CL for Mean	Upper 95% CL for Mean
Planted or Natural								
Natural	267	4.9076	0.1566	6.5506	0.33	15.67	4.5992	5.2160
Planted	25	14.8000	1.1260	31.6945	7.00	28.00	12.4761	17.1239
Crown Class								
Intermediate	11	18.5755	0.9257	9.4262	15.33	24.33	16.5129	20.6380
Suppressed	281	5.2526	0.1875	9.8821	0.33	28.00	4.8835	5.6218
Tree Codes								
No Damage	69	8.8839	0.7252	36.2841	0.33	28.00	7.4369	10.3309
Minor Damage	82	5.7317	0.3370	9.3153	1.33	16.00	5.0611	6.4023
Severe Damage	141	4.2364	0.1619	3.6970	1.33	14.00	3.9162	4.5565
Ecosite								
E2	25	14.8000	1.1260	31.6945	7.00	28.00	12.4761	17.1239
E3	46	4.1815	0.3238	4.8223	1.67	12.33	3.5294	4.8336
F2	179	5.0874	0.1902	6.4773	0.33	15.67	4.7120	5.4628
F3	32	5.0100	0.5680	10.3224	1.33	15.67	3.8516	6.1684
I1	10	4.7000	0.4909	2.4101	3.33	8.67	3.5894	5.8106

7.8 Field sampling quality control

7.8.1 Introduction

From mid-July to early-September field data collection was completed for the project *Projecting height growth of understory Picea glauca in stands with an overstory dominated by Populus tremuloides*.

There were two sampling locations:

- the Boreal sub-region north east of Lac La Biche;
- and the Lower Foothills sub-region south of Edson.

One crew (from the U of A) completed all Lower Foothills measurements. The plots in the Boreal sub-region were collected both by Timberline Forestry Consultants and the U of A crew. To ensure that both crews measured in a consistent fashion, check plots were done by the U of A crew on selected areas sampled by Timberline Forestry Consultants. This report evaluates the differences observed between the measurements taken by the two crews.

7.8.2 Results for sampled overstory

In the Boreal sub-region, Timberline Forestry Consultants measured 147 plots with a total of 1,983 living overstory trees. There were 24 quality control check plots done, with a total of 56 overstory trees sampled. The quality control process involved randomly sampling a maximum of three trees per check plot (some plots had less than three trees in total). The following are summaries, which compare the measured individual overstory tree attributes between original and check plots.

Table 7.16 Summary of Overstory Attributes Measured in the Original Plot and Check Plots

Overstory Tree Attribute	No. of trees	Average Measurement		Variance	Paired T-Test (95%)	
		Original	Check Plot		Critical Value	Calculated Value
Height (m)	47	19.42	19.24	1.215	2.02	1.11
Height to Live Crown (m)	47	13.44	11.97	2.381	2.02	6.56*
Diameter Breast Height (cm)	55	17.61	17.69	0.406	2.00	-0.868
Breast Height Age (yrs)	35	53.09	58.74	106.467	2.03	-3.24*

* - identifies significant difference in measurements

7.8.2.1 Height

Original and check plot height measurements were close with averages of 19.42m and 19.24m respectively (Table 7.16). The variance was low at 1.215m^2 (or standard error = 1.10m). This variability was within an acceptable range.

A paired t-test resulted in a calculated value of 1.11, which suggested no difference in height measurements in original versus check plots (at 95% level of significance). When plotted (Figure 7.13), the relationship was strongly linear with an R^2 value of 0.9537 with variance remaining constant regardless of height. The regression line is precisely on the "1 to 1 relationship diagonal" indicating no difference between check and original plots. Thus, there was no need to adjust height values.

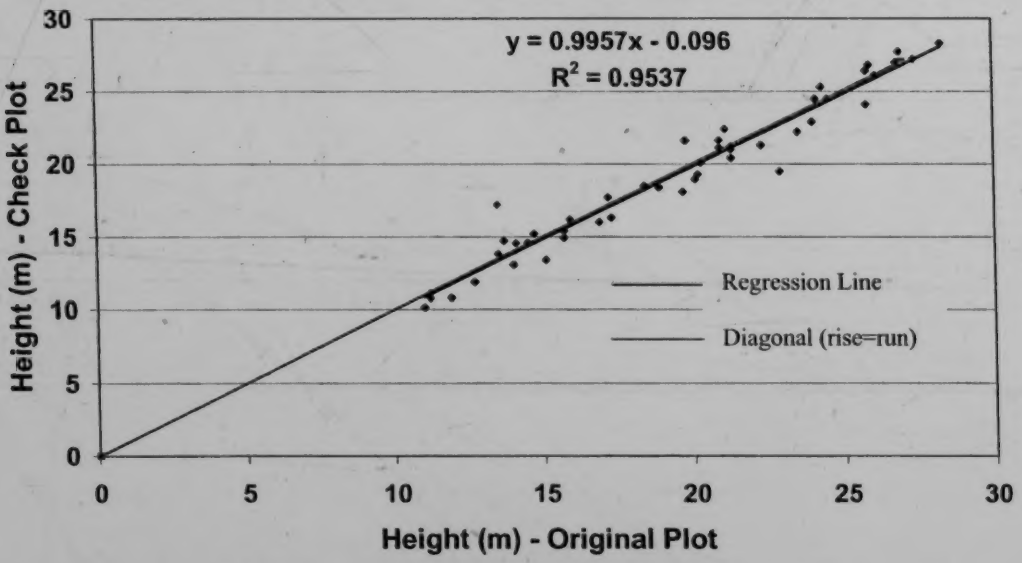

Figure 7.13 Overstory height measurements - original plot versus check plot

7.8.2.2 Height to live crown

There was a moderately high difference in average Height to Live measurements in original versus check plots. The average for the original plots was 13.44m whereas the check plot average was 11.97m (Table 7.16). Variance was also quite high 2.381m^2 (or standard error = 1.54m). This difference was also shown to be strongly significant when a paired t-test was applied (calculated t-value = 6.56 and a critical t-value of 2.02 at a 95% level of significance). These differences were due to the subjective nature of measuring height to live crown. Since the majority of overstory trees measured were deciduous, this subjectivity is exacerbated.

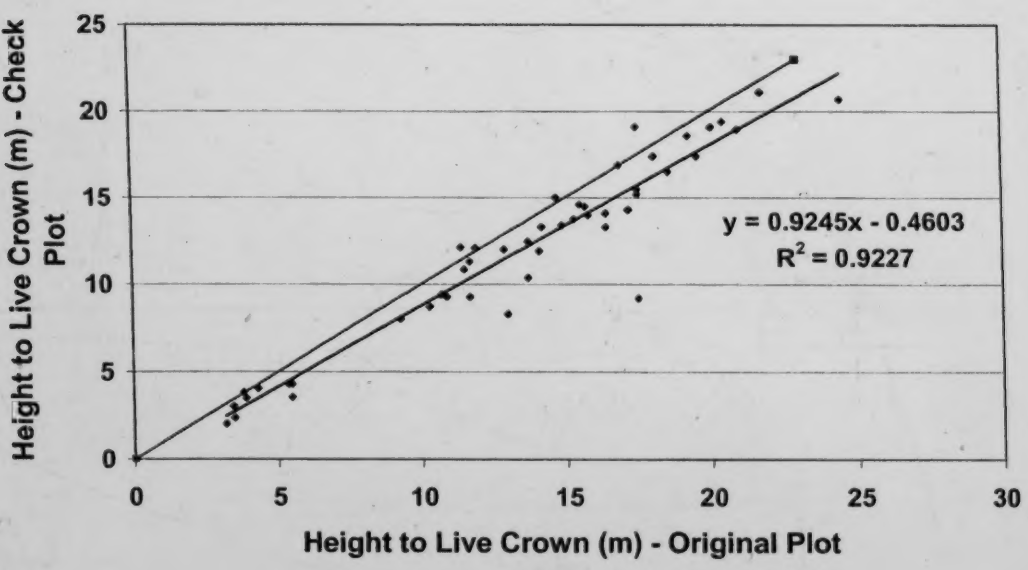

Figure 7.14 Overstory height to live crown measurement - original plot versus check plot

Figure 7.14 showed fairly strong linearity with an R^2 value of 0.9227. Variance remained constant regardless of tree height (except perhaps at heights less than 7m – where it was lower). On average height to live crown was measured at a lower value in the check plot compared to the original plots. This suggested a bias between plot measurements. In general, the check plot crew tended to estimate the starting location of the live crown at a spot somewhat lower than the original crew.

Although each crew viewed height to live crown somewhat differently it appeared each crew applied their definition consistently throughout the sampling process. Therefore, an adjustment factor was applied prior to further analysis.

7.8.2.3 Diameter breast height (DBH)

There was comparatively little difference in DBH measurements taken regardless of the crew sampling. Average DBH measurements were 17.61cm in the original plots and 17.69cm in the check plots. The variance was also very low at 0.406cm^2 (Table 7.16). This similarity was also reflected in a paired t-test. The calculated t-test value was -0.868, which was well below the critical t-value of +/-2.00 at 95% level of significance (signifying no difference).

As well, a regression analysis showed little difference between the two plots (Figure 7.15). Not only is the regression line strongly linear (R^2=0.9927), but it also falls exactly on the line of perfect correlation (the diagonal). The analysis clearly suggested no difference in DBH regardless of sampling crew.

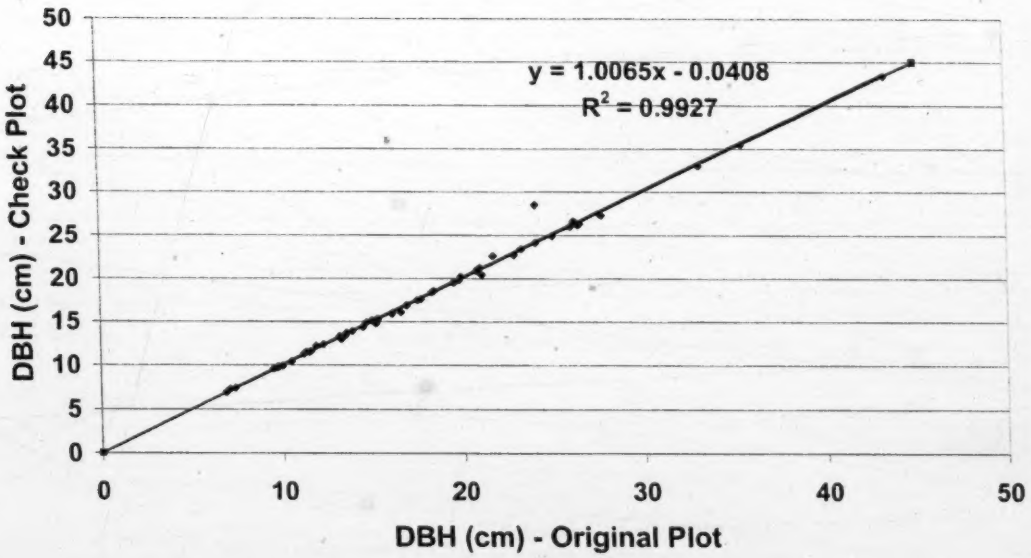

Figure 7.15 Overstory diameter breast height of original plot versus check plot

7.8.2.4 Breast height age

Average age at breast height was 53.09 years for original plots and 58.74 years for check plots. This difference is fairly high, which was also reflecting in the high variance of 106.47 year^2. This suggested that the crews often obtained ring counts quite different from one another on individual trees. A paired t-test showed this difference as well; indicated by a calculated t-value of -3.24 and a critical value +/- 2.03.

A regression analysis showed a relatively weak linear relationship between original and check plot breast height ages - R^2 value of 0.6732 (Figure 7.16), with a fairly high amount of variability. This was somewhat expected because the majority of the aged overstory trees were deciduous. Deciduous trees are often harder to age due to fainter rings and increased levels of rot. This increased difficulty in aging deciduous trees suggested a split between trembling aspen and white spruce overstory trees should be investigated.

This division of coniferous and deciduous trees proved useful, as there was little difference between check and original plots in regard to overstory white spruce breast height age (Figure 7.17). However, breast height age of trembling aspen showed a clear difference between plots (Fig. 8). On average, the check plot crew assigned a higher age for overstory trembling aspen than the original crew. This meant an adjustment factor was applied to trembling aspen breast height ages before further analyses were done. The adjustment factor was applied from ages 30 to 80 (outside this range uncertainty of the accuracy increases). Although this lack of similarity was undesirable, it is not a significant problem for this study because average overstory stand age was used on very limited basis during further analysis.

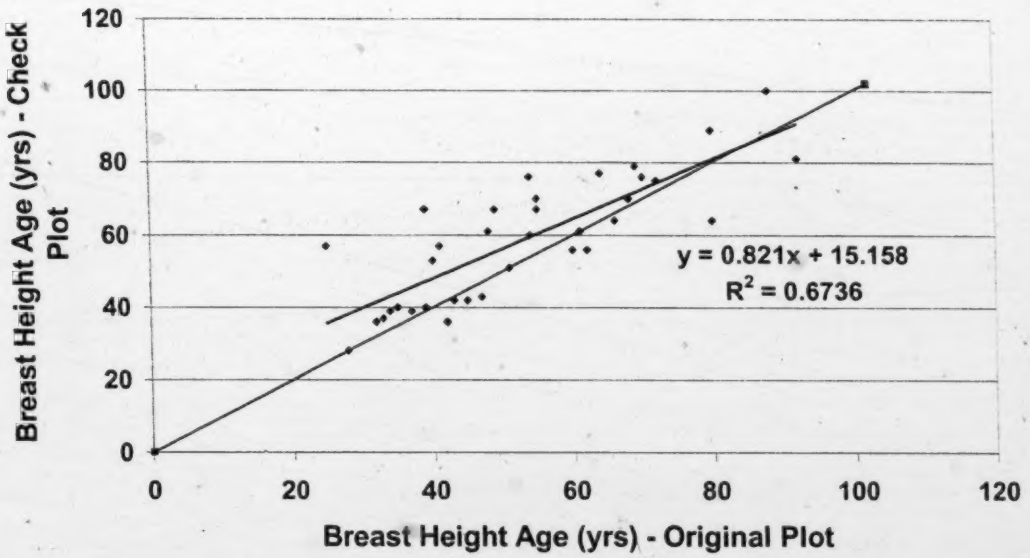

Figure 7.16 Overstory breast height age (both trembling aspen and white spruce) of original plot versus check plot

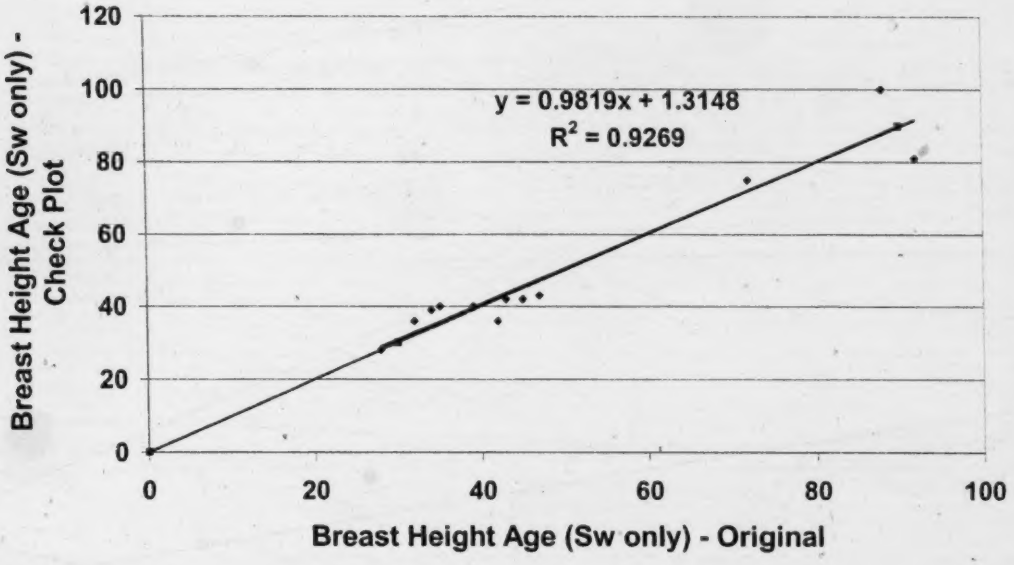

Figure 7.17 Overstory breast height age of original plot versus check plot (white spruce (Sw) only)

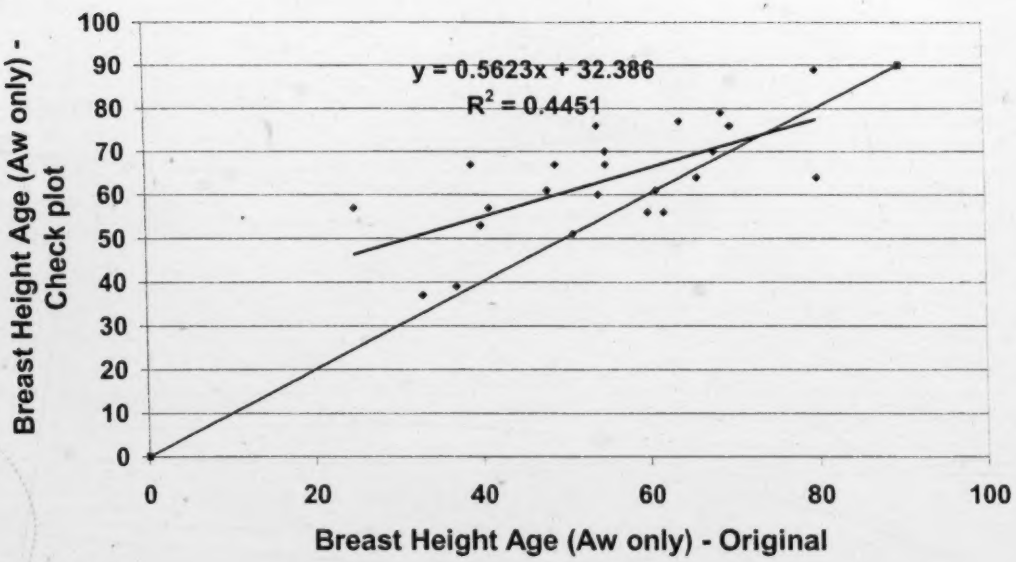

Figure 7.18 Overstory breast height age of original plot versus check plot (trembling aspen (Aw) only)

7.8.2.5 Conclusions

Some differences in measurements taken between sampling crews occurred. Table 7.17 summarizes the results of the variables measured and if an adjustment factor was applied.

Table 7.17 Summary of regression equations and application to further analysis

Overstory Attribute	Adjustment (or Regression) Equation	Adjustment Factor Applied
Height	y = 0.9957(x) - 0.0960	No
Height to Live Crown	y = 0.9245(x) - 0.4603	**Yes**
DBH	y = 1.0065(x) – 0.0408	No
Breast Height Age	y = 0.8210(x) + 15.158	No
Breast Hgt Age - Sw only	y = 0.9819(x) + 1.3148	No
Breast Hgt Age – Aw only	y = 0.5623(x) + 32.386	**Yes**

Note: x – measurements from original plots (Timberline Forestry Consultants)
y - measurements from check plots (U of A Crew)

7.8.3 Results for sampled understory

In the Boreal sub-region, Timberline Forestry Consultants measured 147 plots with a total of 1867 individual understory white spruce trees. A total of 24 quality control plots and a total of 55 individual understory white spruce trees, were measured. The quality control process involved re-measuring a maximum of three trees per plot for each of the 24 plots. The following summary compares the measured individual understory white spruce attributes between original and check plots.

Table 7.18 Summary of understory white spruce attributes measured in the original plot and check plots

Understory Attribute	No. of trees	Average Measurement		Variance	Paired T-Test (95%)	
		Original	Check Plot		Critical Value	Calculated Value
Height (m)	55	4.70	4.67	0.210	2.00	0.54
Height to Live Crown (m)	55	2.16	1.81	0.618	2.00	3.23*
Root Diameter (cm)	18	1.18	1.05	0.008	2.11	6.01*
Diameter Breast Height (cm)	35	6.67	6.66	0.024	2.03	0.55
Stump Age (yrs)	19	18.53	20.42	37.099	2.10	-1.36
Breast Height Age (yrs)	24	33.54	35.92	27.375	2.07	-2.24*
Three Year Increment (cm)	26	32.44	31.27	143.692	2.06	0.50

* identifies significant difference in measurements

7.8.3.1 Height

Original and check plot height measurements were similar with averages of 4.70m and 4.67m respectively (Table 7.18). The average difference between the two measurements was 0.03m with a variance of 0.210m^2 and a standard error of +/- 0.46m.

A paired t-test resulted in a 0.54 t-value, which suggested no difference in height measurements between original and check plots (at 95% level of significance: n=54). The strength of the relationship was also reflected in a regression analysis, showing a strongly linear relationship (R^2 = 0.9899 – Figure 7.19). As was expected there was an increase in variance as height increased. There was no need for any adjustment to heights based on sampling crew.

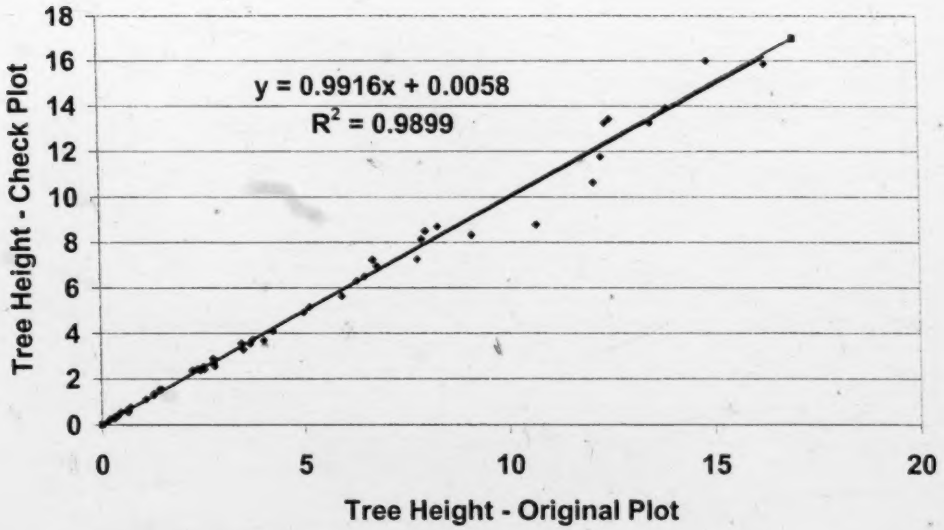

Figure 7.19 Understory white spruce height - original plot versus check plot

7.8.3.2 Height to live crown

There was a relatively large average difference in height to live crown measurements in original versus check plots. The average for the original plots was 2.16m whereas the check plot average was 1.81m, which resulted in an average difference of 0.35m (Table 7.18). This large difference was shown to be significant when a paired t-test was applied. A t-value of 3.23 was calculated which was greater than the critical t-value of 2.00 at a 95% level of significance (n=54).

These differences while undesirable were not unexpected because height to live crown is a subjective measurement. For this project the following definition of height to live crown was defined as the vertical distance (in metres) from the germination point to the base of the live crown. The base of the live crown is the lowest point on the bole where the canopy is relatively uniform. This definition can lead to different interpretations as to what "relatively uniform" means. Perhaps a more explicit definition would have avoided this.

Regardless, a regression analysis showed a fairly strong linear trend (R^2 = 0.9226). Just as in total height measurements, an increased variance in height to live crown measurements was observed as height to live crown increased. For the most part, the check plot estimate of height to live crown was lower than the original plot. Although there was clearly a difference in measured height to live crown between crews, it appeared to have been applied consistently throughout the sampling process. Prior to further analysis an adjustment factor was applied.

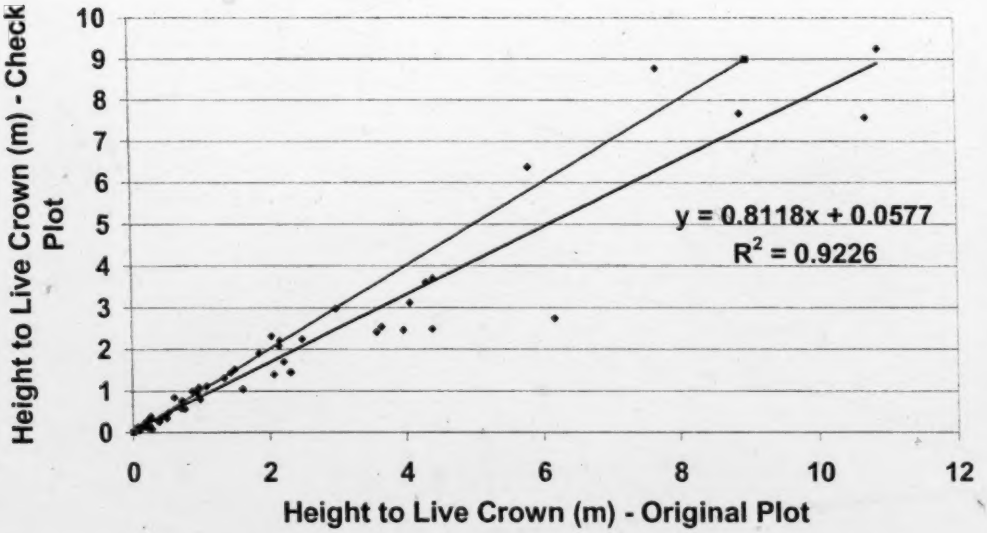

Figure 7.20 Understory white spruce height to live crown - original plot versus check plot

7.8.3.3 Root collar diameter

During field data collection, root collar was measured by taking the average of two measurements using calipers at right angles. A small difference in average root collar measurements between original and check plots (1.18cm and 1.05cm – respectively) was observed, for an average difference per observation of 0.13 cm. This is an average difference of just over 1mm per observation.

Despite the small difference between averages, a paired t-test showed a substantial bias in the sampling as a t-value of 6.01 was calculated which was greater than the critical value of 2.11 at a 95% level of significance (n=17). This suggested a difference in root collar diameter measurements between crews.

Despite a large t-value, the relationship was strongly linear ($R^2 = 0.9749$) (Figure 7.21). Variance also appeared to stay fairly consistent regardless of diameter size. A careful look at the data points revealed that the average root collar size of the check plot was consistently lower than that of the original plot. There were two likely reasons for this: 1) the crews were consistently measuring root collar at different places on the stem or; 2) the check crew was more aggressive at firming up the measuring calipers before a measurement was taken. On the basis of these results, an adjustment was applied to all root collar diameter measurements.

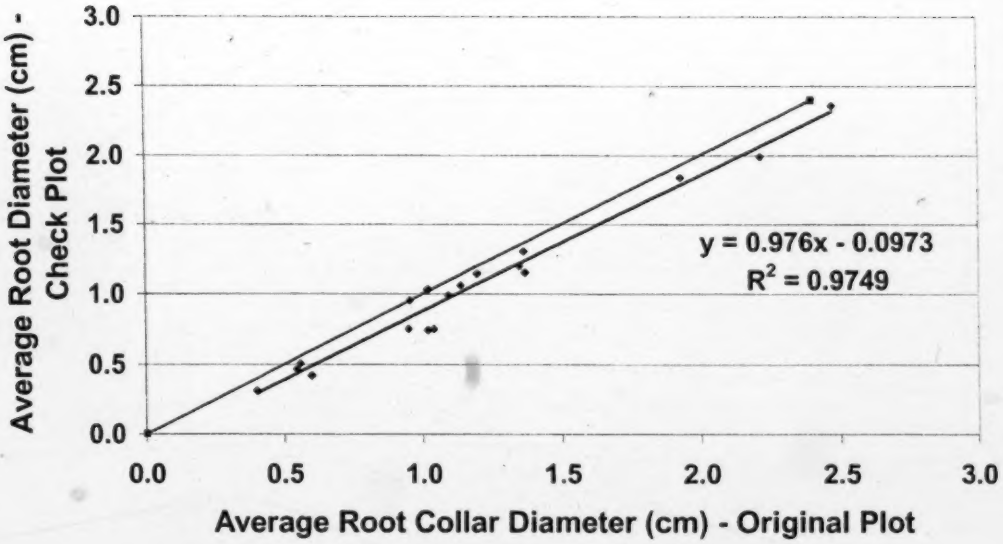

Figure 7.21 Understory white spruce root collar diameter - original plot versus check plot

7.8.3.4 Diameter breast height (DBH)

The average measurements of DBH for the original and check plots were very similar, 6.67cm and 6.66cm respectively (Table 7.18). The variance between measurements was also quite small at 0.024cm^2. This result was also reflected in a paired t-test. The t-test value was 0.55, well below the critical t-value of 2.03 at 95% level of significance (n=34). A regression analysis (Figure 7.22) showed no bias in measurement.

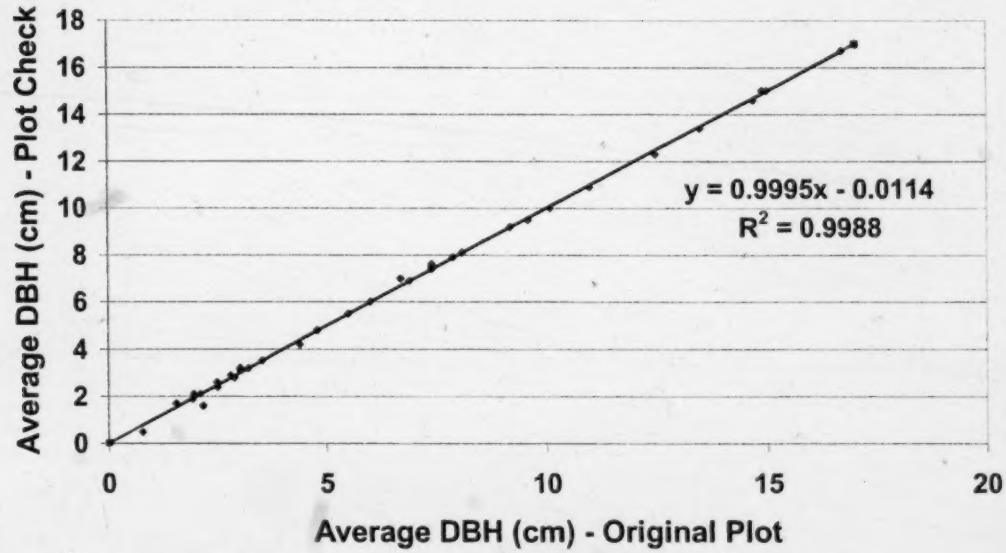

Figure 7.22 Understory white spruce diameter breast height - original plot versus check plot

7.8.3.5 Stump age

Only 19 understory trees had stump height (0.3m) age measurements taken in both the original and check plots. As is sometimes expected when aging trees in the field, there was some variability in the values (relatively high variance of 37.099 yrs^2). A paired t-test resulted in a calculated t-value of –1.36. When the t-value and variance were considered together, the data suggested that although the stump age variance is large, bias was not evident.

Of all the values measured stump height age had the weakest linear relationship between original versus check plots (Figure 7.23). Clearly at greater than 20 years, stump age measurements had increased variability. Although this was cause for concern, the relationship appeared to be unbiased. This large variance can be somewhat explained as spruce can often take a number of years to grow from stump height (0.3m) to breast height (1.3m); this results in very "tight" rings at stump height that are difficult to count. Thus, although the variance is not as low as desired, the values can still be used with care in further analysis. Without clear indication of bias in the samples an adjustment factor will not be used.

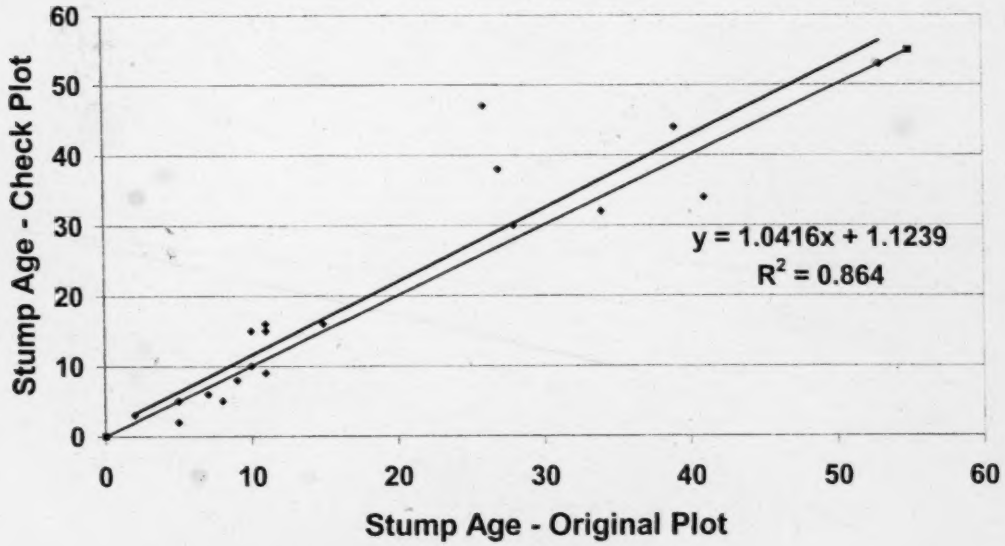

Figure 7.23 Understory white spruce stump age - original plot versus check plot

7.8.3.6 Breast height age

The average age at breast height was 33.54 years and 35.92 years for original and check plots respectively. A paired t-test resulted in the rejection of the null hypothesis (t = -2.24), suggesting breast height age measurements differed between crews.

The linear relationship between original and check plot breast height ages was strong (R^2 value of 0.9595 - Figure 7.24). However, a measurement bias can be seen; at higher ages (>45 years) the check plot crew on average counted more rings than the original crew, while from 0 to 45 years both original and check plots values are similar.

To evaluate this difference above and below 45 years two separate regression analysis were run with only those points above or below 45 years. Below 45 years the regression line was close to the diagonal, meaning that below 45 years there was no need for adjustment (Figure 7.25). Above 45 years the regression line runs parallel to the diagonal however, it is about 8 years higher than the diagonal. Therefore, above 45 years the adjustment was applied (Figure 7.26).

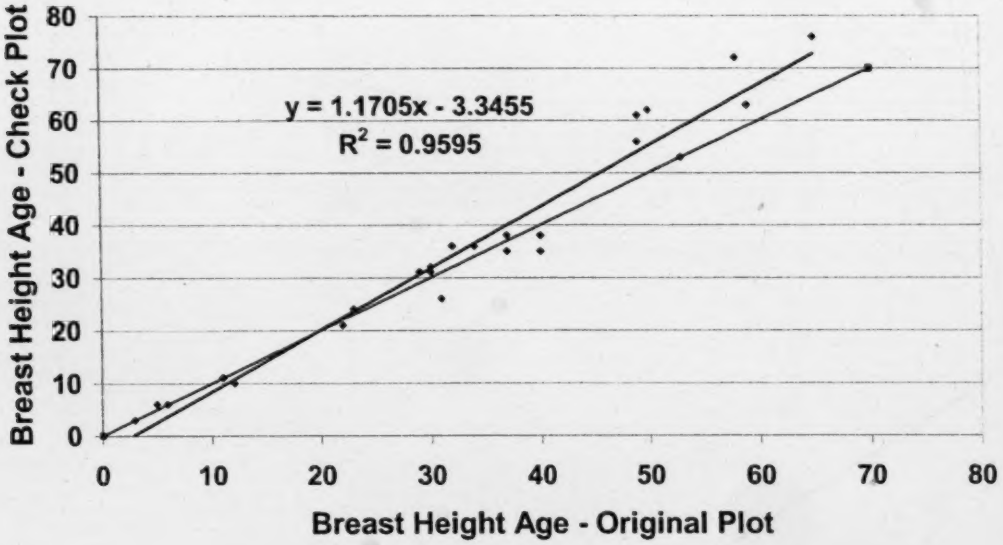

Figure 7.24 Understory white spruce breast height age - original plot versus check plot (all points)

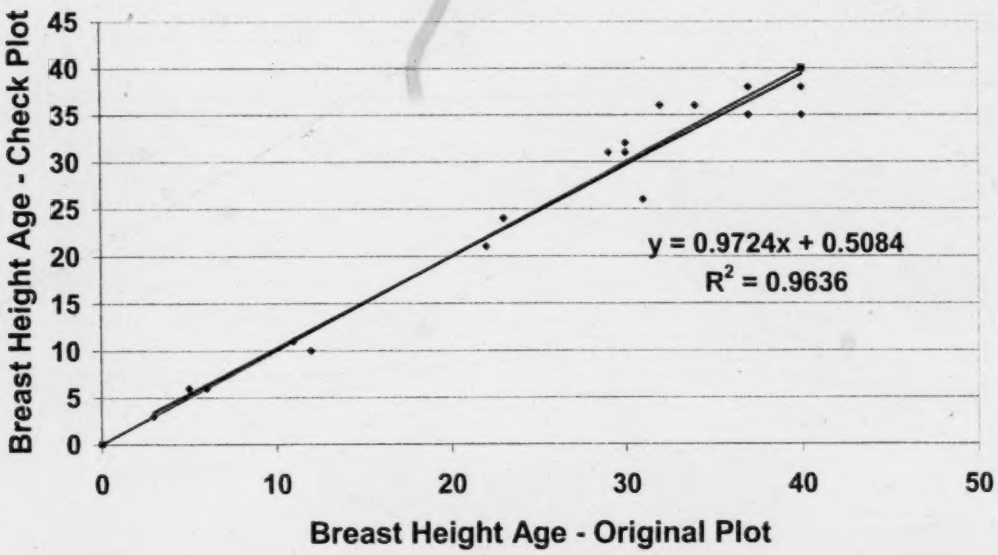

Figure 7.25 Understory white spruce breast height age - original plot versus check plot (points less than 40 only)

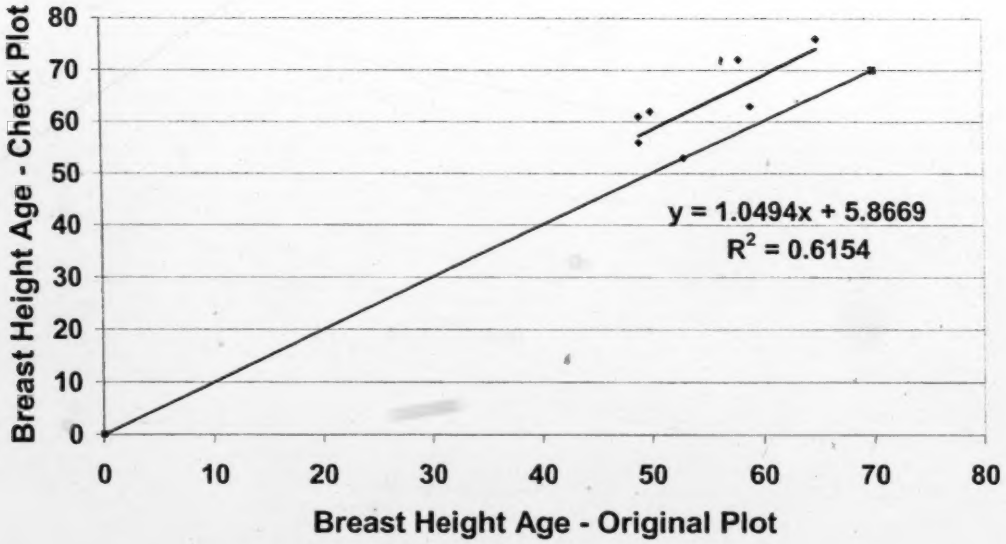

Figure 7.26 Understory white spruce breast height age - original plot versus check plot (points greater than 40 years only)

7.8.3.7 Three year height increment

When comparing the estimates of three-year height increment measurements between original and check plots the values appeared initially close with values of 32.44cm and 31.27cm respectively. However, this was accompanied with a large variance of 143.692cm^2 (Table 7.18). A paired t-test resulted in a calculated t-value (0.50) well below the 2.06 critical value at 95% significance. This low t-value is somewhat misleading due to a large variance. The large variance is primarily caused by one set of values that was radically different (Figure 7.27).

When the outlier was removed the comparison statistics greatly improved. Variance dropped dramatically to 9.743cm^2. A test still showed no significance with a calculated t-value of –1.762. The regression analysis also improved from an R^2 of 0.814 to an R^2 of 0.991 (Figure 7.28), showing a strongly linear relationship.

When individual points were examined many trees received the same measurement in both original and check plots. This was especially true when average three-year increment was greater than 20cm (excluding the outlier). This meant that an adjustment factor is not needed.

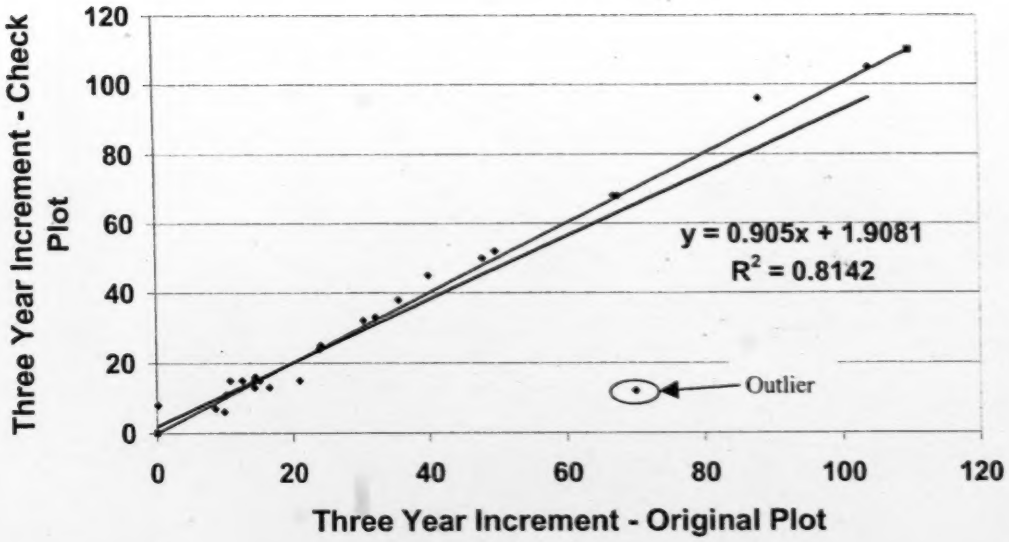

Figure 7.27 Understory white spruce three year increment - original plot versus check plot (outlier included)

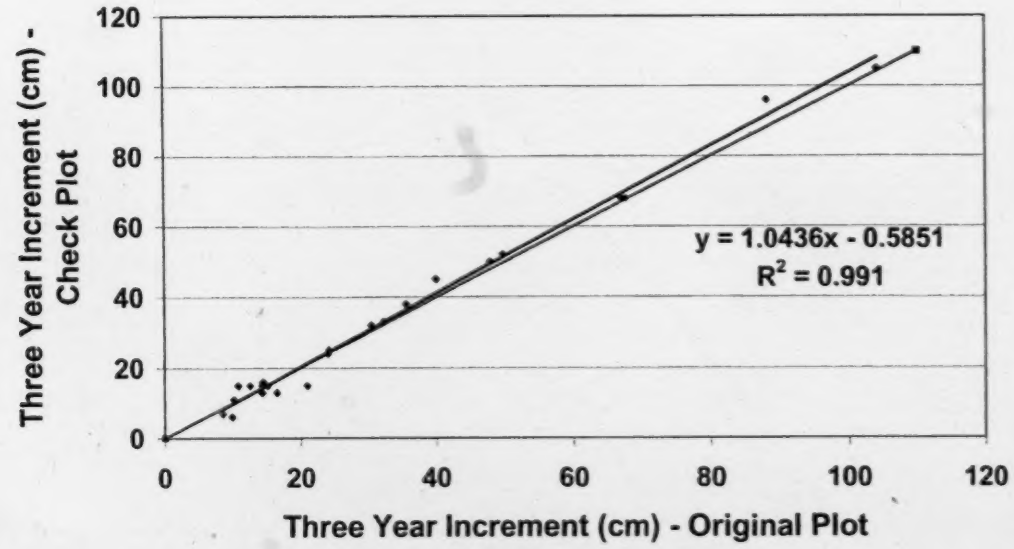

Figure 7.28 Understory white spruce three year increment - original plot versus check plot (outlier removed)

7.8.3.8 Conclusions

Some differences between sampling crew measurements were observed. Table 7.19 summarizes the results of the variables measured and if an adjustment factor should be applied.

Table 7.19 Summary of regression equations and application to further analysis

Understory Attribute	Adjustment (or Regression) Equation	Adjustment Factor to be Applied
Height	$y = 0.9916(x) + 0.0058$	No
Height to Live Crown	$y = 0.8118(x) + 0.0577$	Yes
Root Collar Diameter	$y = 0.9760(x) - 0.0973$	Yes
Diameter Breast Height	$y = 0.9995(x) - 0.0114$	No
Stump Height Age	$y = 1.0416(x) + 1.1239$	No
Breast Height Age	$y = 1.1705(x) - 3.3455$	No
Breast Height Age (0 – 45 years)	$y = 0.9724(x) + 0.5084$	No
Breast Height Age (greater than 45 years)	$y = 1.0494(x) + 5.8669$	Yes
Three Year Increment	$y = 0.9050(x) + 1.9081$	No

Note: x – measurements from original plots (Timberline Consultants)
y - measurements from check plots (U of A Crew)

An adjustment factors was applied to the following understory attributes:

- Height to Live Crown
- Root Diameter
- Breast Age (greater than 45 years)

7.9 Detailed field sampling procedures manual

This is a copy of the field sampling procedures used during the sampling component undertaken during the summer of 2000.

7.9.1 Project overview

This manual describes the field procedures for the University of Alberta Project *Projecting height growth of understory Picea glauca in stands with an overstory dominated by Populus tremuloides*. The project studies the vigor of white spruce growing under predominately deciduous canopies.

7.9.2 Field personnel

Field sampling staff will be comprised of 4 people (formed into two 2-person crews). The University of Alberta will supply one crew, as will Timberline Consultants.

To ensure all participants understand the sampling procedures, a two-day training session will be held just before the start of field data collection (perhaps July 13 and 14 or the 17 and 18).

7.9.3 Shifts

The fieldwork will be completed in 30 working days, which requires three shifts of 10 working days followed by 4 days off. Each workday will be 10 hours in length (suggested start at 7:30 am). The proposed shifts are as follows:

Shift #1: July 17 – July 26
Shift #2: July 31 – August 9
Shift #3: August 14 – August 23

* - a portion of a 4th shift may be required depending on the number of rain days.

7.9.4 Field equipment

Each crew requires the following items while sampling:

1 – clinometer
2 – compasses
1 – metal diameter tape
1 – set of calipers
1 – 30m loggers tape
1 – topophil
1 – hip chain
1 – hand lens
1 – loggers crayon or tree paint
1 – increment borer
several plot tally sheets
1 – first aid kit

2 – sets of bear bangers with flares
2 – hard hats (if required)
1 – chain saw safety equipment (if chain saw is being used)
2 – ATV helmets (when using an ATV)
1 – set of metal poles to mark plot centers
1 – GPS unit
1 – cell phone or some other form of portable communication
several metal tags to attach to mark plot centre number and location
flagging tape
markers, pens, and pencils

7.9.5 Overall field design

A stand was deemed eligible for sampling if it met the requirement of having an AVI call of predominately (>80%) deciduous overstory with spruce in the understory. A random selection process was used to choose the stands to be sampled. Each crew will be assigned a list of sites to sample along with needed access maps.

Although it is desired that sample sites are randomly selected, it is acknowledged that some areas may be impossible to access by quad. Therefore, a list of potential alternative sampling locations will be assigned to each crew as well. These sites can be used when an assigned sampling area cannot be accessed. The alternative sample site selected should be based on similarity to the desired sample area and access.

A cluster of 3 circular 100 m2 fixed area plots (see figure 1 below) will be placed in each stand to be sampled.

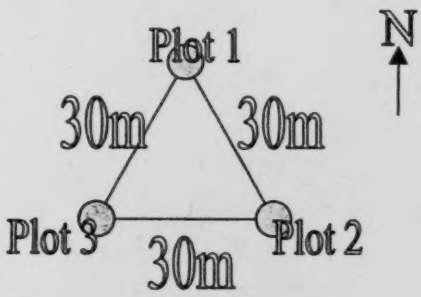

Figure 1. Plot Cluster Layout

It is expected that each of the sampling crews will average completing 1 and 2/3 of these plot clusters per day (including quality control). This will result in an estimated total of 100 plot clusters or about 300 plots measured during the expected 30 days of data collection for this project.

7.9.6 Selection of plot location

The location of the plot cluster within a chosen stand was positioned randomly. The procedure for locating the plot cluster involved placing a 40m x 40m grid over the stand and sequentially assigning a number to each grid box (see fig 2). A grid box will then be randomly selected.

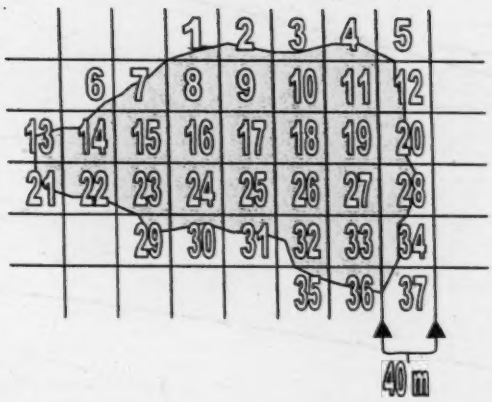

Figure 2. Stand Grid System Used to Randomly Locate Plot within Stand.

A selected grid box means that at least one plot (and if possible all 3) to be placed within the grid location. For example, if grid 27 was selected the entire plot cluster could be contained within the grid. However, only one plot (or a portion of one plot) could fit into grid 37, with the other two plots being placed likely in grid 33 and 36.

The location of each plot cluster will be marked on an access map. To enable locating the sampling locations on the ground, a suggested tie point will be assigned along with the bearing and distance to the centre of the first plot for each plot cluster.

7.9.7 Plot cluster location and lay-out procedures

1. On the map locate a tie-point and ensure that it is clearly marked on an access map.
2. On the ground clearly flag the tie-point, ensuring that the distance and bearing from the tie-point to the center of plot 1 has been clearly marked (by writing on the flagging).
3. The line followed to plot 1 from tie point should be well flagged to enable easy location of the plot at a later time.
4. The plot center will be marked with the project, plot cluster #, plot #, and date to ensure that it can be found again for quality control checking and follow-up measurements.
5. From plot centre measure a distance of 5.64 metres ($100m^2$ plot) in a due north direction.
6. All plot level measurements are taken at this time (LAI 2000, estimations of Plot Species composition and Crown Closure)
7. Plot sweeps will move in a clockwise direction with measurements made on each understory and overstory tree as they are arrived at.
8. In denser plots, to ensure no double counting, each tree should be "flagged" (or marked with a loggers crayon) as it is measured.
9. Complete destructive sampling (if any).
10. Upon completing plot #1, a measurement of 30 m @ bearing 150 degrees will be done to locate plot centre 2.
11. Repeat steps 4 to 9.
12. Upon completing measurements of plot 2, then a measurement of 30 m @ bearing 270 degrees will be done to locate plot centre 3.
13. Repeat steps 4 to 9.
14. Plot cluster measurements complete.

7.9.8 When is a tree considered in a plot?

The decision of whether a tree is in or out of a plot is based on the point of germination. If a tree's point of germination is within the plot, the tree is considered within the plot regardless if the majority of the tree is leaning outside the plot. Therefore, the opposite will be true as well.

7.9.9 Plot measurements

A series of measurements will be taken at each plot, and recorded on a standardized tally sheet (see Section 7.9). Each of the fields on the tally sheet are explained below:

7.9.9.1 Plot information

1. Plot Cluster # - A unique number assigned to each plot cluster.
2. Plot # - A unique number assigned to each plot within a plot cluster (1,2, or 3).
3. TWP - Township plot is located in.
4. RG - Range plot is located in.
5. M - Meridian plot is located in.
6. Stand - AVI Stand number plot is located in.
7. Date – Date that the plot was sampled, recorded in the month/day format.
8. Crew – Initials of the crewmembers that measured the plot.

7.9.9.2 Plot measurements

1. Northing – GPS north coordinate taken at plot centre (recorded on a data logger)
2. Easting – GPS east coordinate taken at plot centre (recorded on a data logger)
3. Light Measurements – Light measurements will be taken at the center of each plot using a LICOR LAI-2000 Plant Canopy Analyzer, with a 180° view restrictor fitted onto the sensor head. Two readings are required at the center of each plot, one is taken with the sensor head pointing towards the west (270°) and one is taken with the sensor head pointing east (90°). Measurements must be taken with the sensor leveled and pointing away from the sun, in order to avoid direct sunlight hitting the sensor. Consequently, unless measurements are taken under overcast sky conditions, it is necessary to take readings with the sensor pointing to the west in the morning, and readings with the sensor pointing east in the afternoon.

   Matching open sky readings (using a single LAI-2000 sensor and datalogger package) will be taken as the below canopy readings are taken at plot center. Open sky readings must be taken within 5 minutes or less of the plot center measurements.

When taking measurements using these sensors, plot cluster number is entered as "SITE" in the datalogger, and plot number and bearing (e.g. 1-270) is entered for point. For open sky readings plot cluster number is entered for "SITE" and "A" and the bearing are entered for point (e.g. A-270).

The LAI-2000 datalogger should be downloaded to a laptop computer each evening following measurement (at a minimum they should be downloaded every 3 days).

4. Clear or Overcast – A general description of the sky at the time of sampling with the light sensor. Possible classifications are:

   Clear – Less than 20% cloud cover
   Partly Cloudy – Between 20% and 80% cloud cover
   Overcast – Over 80% cloud cover

5. Ecosite – Ground call ecosite as per the *Field Guide to Ecosites of Alberta* Series. Each ecosite will be recorded based on natural sub-region followed by ecosite classification and ecosite phase and finally plant community type (where applicable). An example would be LF – E3.4, which means Lower Foothills sub-region, the ecosite and ecosite phase are E3 meaning Low-bush cranberry Aw-Sw-Pl, and plant community type 4.

   Abbreviations to be used for natural sub-regions are as follows:
   LF – Lower Foothills sub-region
   UF – Upper Foothills
   MN – Montane
   BM – Boreal Mixedwood
   BH – Boreal Highlands

   Abbreviations to be used for ecosite, ecosite phase and plant community are the same abbreviations as are used in the *Field Guide to Ecosites of Alberta* series.

6. Overstory Species and Composition Percentage – Ground call estimation of overstory species and percentage composition in the general area around the stand. An example is a call of Aw8Bw1Sw1, which means of the trees on the plot 80% are trembling aspen, 10% are white birch, and 10% white spruce.

7. Overstory CC – Ground call estimation of Overstory Crown Closure measured to the nearest 5%.

8. Understory CC – Ground call estimation of Understory Crown Closure measured to the nearest 5%. Understory crown closure will be estimated at both the height of 1.3 m and at ground level.

7.9.9.3 Overstory measurements

1. T# - Tree number sampled
2. Sp – Overstory Tree Species

Tree species will be recorded by using the standardized Alberta abbreviations. Although, the majority of the overstory species sampled will be trembling aspen *(Populus tremuloides)* (and maybe *Populus balsamifera*) it is important to record all overstory species (including spruce).

Common Name	Genus/Species	Species Code
Trembling aspen	Populus tremuloides	Aw
Balsam poplar	Populus balsamifera	Pb
White spruce	Picea glauca	Sw
Black spruce	Picea mariana	Sb
Engelmann spruce	Picea engelmannii	Se
Alpine fir	Abies lasiocarpa	Fa
Balsam fir	Abies balsamea	Fb
Lodgepole pine	Pinus contorta	Pl
Jack pine	Pinus banksiana	Pj
Limber pine	Pinus flexilis	Pf
Whitebark pine	Pinus albicaulis	Pw
White birch	Betula papyrifera	Bw
Tamarack	Larix laricina	Lt
Western larch	Larix occidentalis	Lw
Alpine larch	Larix lyallii	La
Douglas-fir	Pseudotsuga menziesii	Fd

3. Hgt – Tree Height

Three tree heights must be measured (to the nearest $1/10^{th}$ metre by either clinometer, height pole, or metre tape). If possible the heights should be taken on 1 dominant and 2 co-dominant trees. Note: all site trees must be measured and may count as one of the measured trees per plot.

4. Hgt to Live Crwn – Height to Live Crown

Measurements of height to live crown should be taken on 3 overstory trees (1 dominant and 2 co-dominant if possible). Height to live crown is the vertical distance (in metres) from the germination point to the base of the live crown. The base of the live crown is the lowest point on the bole where the canopy is relatively uniform. The intent of this information is to determine where crown break-up is occurring. Thus, this measurement should not be influenced by isolated lower live branches. It should be recorded to the nearest 1/10 m by directly measuring or visually estimating.

5. This column was removed

6. DBH – Diameter Breast Height

The DBH of each overstory tree will be measured with a diameter tape at the standard height of 1.3 metres from the germination point. If it is not possible for an accurate measurement to be taken with a diameter tape then calipers may be used. However, when using calipers two measurements (at right angles) must be taken (1 and 2 – on the tally sheet). Only one measurement will be recorded when using a D-tape.

7. Crn Cls – Crown Class

A call of crown class must be made on each overstory tree with in a plot. Crown class is a description of the location of a tree within a canopy. The possible classifications for this category are as follows:

D – Dominant – The trees that extend above the general canopy level.
C – Co-Dominant – The trees that are at the general canopy level.
I – Intermediate – The trees moderately below the general canopy level but beginning to reach up into the base of the main canopy.
S – Suppressed – The trees well below the general canopy level.
V – Veteran – Tree appears to be significantly older than the majority of the stand. This classification usually refers to a tree that survived the last stand destroying event.

8. Age – Overstory tree age at breast height

At least three overstory trees will be aged for each plot cluster (including site trees). Age will be collected at breast height (1.3 m) with an increment core. If the sample tree is too small to core than age will be assessed by counting whorls. As there is often difficulty in accurately aging trees by counting whorls. When this method is used predominately in a plot, age will be further checked by destructively sampling at least one tree per plot. Rings will be counted and recorded in the field, then stored and brought to the U of A for further analysis with a microscope. Only trees that are either dominant or co-dominant are eligible for age sampling.

9. Def. - Defect

A general description of defect is to be assigned to each overstory tree. The following descriptions are to be assigned:

N – No Defect.
M – Minor Defect. Tree has minor defects visible. Minor defects do not have significant impact on growth rates, thus a tree classified as having a minor defect should not exhibit traits of being suppressed. Examples of minor defects include closed scars, open scars, loss of current year's leaf cover, and death of current year's leader growth.
S – Severe Defect. Tree has major defects. Major defects have potentially significant impacts on growth rates or show symptoms of being suppressed in the past. Examples of major defects include stem defects (crooks, forks, sweeps, broken tops), girdling, and stem disease.
D – Dead – Tree is standing dead

10. Site Tree

Site trees are used to quantify site quality. In each plot cluster, 3 site trees will be measured (if possible) for both trembling aspen *(Populus tremuloides)* and white spruce *(Picea glauca)*. A tree is eligible to be a site tree if it is Dominant or Co-dominant and free of any major damage and it must not be a veteran. For each site tree height (measured), diameter and age at breast height must be recorded.

When possible, site trees should be taken from within the plot. However, when there are not 3 site trees within the plots, additional site trees can be taken from the inner triangle area formed by the three plot centres.

Codes in the field are as follows:

I – Identified site tree is **inside** one of the three circular 100m^2 plot.
O - Identified site tree is **outside** one of the three circular 100m^2 plot, but is still within the triangle formed by the three plots.

11. Comments

This section is to be used to record additional information about the tree if necessary.

7.9.9.4 What to do if the tree is forked below breast height?

When a tree is forked below breast height treat as two separate trees. However, indicate which trees are on the same stump in the comments section by recording SS (followed by the observation #). Therefore, if SS7 is recorded in the comments section for tree 8, which means that tree 8 is on the same stump as observation 7.

7.9.9.5 Understory white spruce measurements

The columns of DBH, Crown Class, Tree Codes, and Comments are to be measured in the same manner as for the overstory trees. Thus, only the columns where the understory measures differ from the overstory measurements are mentioned below.

2. N/P – Natural regeneration or planted

A call must be made on each understory white spruce as to whether it was planted or naturally regenerated. It will be assumed that all understory trees are naturally regenerated unless there is evidence that it had been planted. The main evidence for planting is scarification that can still be identified (or is known to have occurred from silvicultural records) and the tree is located within the scarification or in a pattern consistent with planting.

When non-spruce understory trees are present, than use this column to identify the species. All understory species will be recorded (see overstory species section for codes to be used); however only on white spruce will all field measurements be performed. All other species will only be recorded as being present.

The options for this field are then:
N – Natural White Spruce
P – Planted White Spruce
Species – Non-white spruce species abbreviation

3. Hgt – Height

Total tree height for all understory spruce must be measured by using a clinometer, height pole, or a tape measure.

4. Hgt to Live Crwn – Height to Live Crown

A measurement of height to live crown will be done in the same manner as for overstory trees. At least three trees will be measured and others can be visually estimated.

5. Root - Root Collar Diameter

Tree root collar diameter measured to the nearest mm. Measurements will be done with either a diameter tape or calipers. If calipers are used two measurements must be taken at right angles, when a diameter tape is used only 1 measurement is needed.

7. Age – Stump height (0.3 m) age and Breast height (1.3m) age

Stump height age will be collected for all samples and when possible, so will breast height age. If a sample tree is large enough, an increment core will be taken for aging. Otherwise, whorls will be counted. As there is often difficulty in accurately aging trees by counting whorls. When this method is used predominately in a plot, age will be further checked by destructively sampling at least one tree per plot. Rings will be counted and recorded in the field, then stored and brought to the U of A for further analysis with a microscope.

9. 3yr Inc – 3 year growth increment

The last 3 years of leader whorls will be counted to measure the height growth over the last 3 years.

9. Tree Codes – Tree Condition Codes

Tree condition codes are a measurement of the health or quality of a tree. For each tree a condition code must be supplied for the bole, the leader, and the canopy. For this project each of the above terms are defined as follows:

Bole – The portion of the tree including the roots and main stem excluding the last 3 years of growth begins.

Leader – The portion of the tree starting from the terminal leader including the last 3 years of growth.

Canopy – Is defined as that portion of the tree other than the bole and the leader. Therefore, the branches and leaves constitute the canopy.

Bole Codes		
Condition Code	Full Title	Description
X1	Standing Dead Condition 1	Tree is dead. It is still standing with the majority (>75%) of its needles present. Tree will be assumed to have been dead for less than 2 years.
X2	Standing Dead Condition 2	Tree is dead. It is still standing and has between 30% and 75% of its needles present. Tree will be assumed to have been dead for 2 – 4 years.
X3	Standing Dead Condition 3	Tree is dead. It is still standing and has less than 30% of its needles present. Tree will be assumed to have been dead for +5 years.
D1	Dead & Down Condition 1	Tree is dead and down. It is has 75%+ of its needles present and the stem wood is sound. Tree will be assumed to have been dead for less than 2 years.
D2	Dead & Down Condition 2	Tree is dead and down. It is has between 30% and 75% of its needles present and the stem is reasonably sound. Tree will be assumed to have been dead for 2 – 4 years.
D3	Down & Down Condition 3	Tree is dead and down. It has less than 30% of its needles present and or the wood is not sound. Tree will be assumed to have been dead for +5 years.
CD	Cut Down	A tree that was within the plot that has been cut down. These trees are identified by the presence of a stump. When this call is made an estimate of time harvested should be made (record in the comments section) based on the soundness and appearance of the stump wood.
BS	Broken / Missing Stem	Stem is broken or missing at a point where more than the previous year's growth is missing.
CK	Crook / Sweep	Stem has a pronounced crook or sweep.
FK	Fork	Stem is forked at a point above breast height (see below for what to do when stem is forked below breast height).
SL	Slight Lean	Tree is leaning at greater than 20° but less than 45°angle.
HL	Heavy Lean	Tree is leaning at a 45°+ angle.
GI	Girdled	Main stem has been girdled.
RD	Root Damage	Tree has root damage (i.e. Armillaria root rot)
OS	Open Scar	Stem is wounded through to the cambium (and has not healed)
SG	Stem Galls/Burls	Galls or burls are present on the stem.
FH	Frost Heave	Evidence of frost heaving.
CS	Closed Scar	Previously, the stem was wounded through to the cambium, however enough time has past since injury that tree has healed the wound.
CO	Conks	Conks are visible on the stem.
SP	Snow Press	Tree has been pressed due to the wait of the snow.
OK	No Defect	Tree bole and stem has no visible defect.
Leader Codes		
Condition Code	Full Title	Description
BT	Broken / Missing Top	This year's growth has been broken or is missing. This indicates that a new terminal leader will "take over" in subsequent years.
DT	Dead Top / Die Back	The terminal lead and a portion of the stem below are dead.
NL	New Leader	The tree has an established leader, however it appears that the previous terminal lead either died or was broken off.
ML	Multiple Leader	Tree has two or more leaders "vying for dominance".
OK	No Defect	Leader has no visible defect
Canopy Codes		
Condition Code	Full Title	Description
SL	Severe Leaf Loss	At least 50% of leaves/needles are damaged
ML	Moderate Leaf Loss	Between 20% and 50% of the leaves/needles are damaged
BG	Branch Galls/Burls	Galls/Burls are present on the branches
MT	Mistletoe	Mistletoe present
WB	Witches Broom	Witches broom present on tree
PV	Poor Vigor	Tree has general poor vigor that does not fit into one of the above categories.
OK	No Defect	Canopy has no visible defect.

Each tree condition code must be three letters in size. The first two are based on the table above that describes the nature of the damage for a tree. The last letter in the code is used to describe the potential agent. Only one tree condition code is to be assigned for each of the bole, leader, and canopy thus, if multiple codes apply to a tree only assign the highest on the list.

Agent of Damage Code		
Code	Full Title	Description
A	Animals	Examples of animal damage are beavers, girdling from squirrels or rabbits, and moose browsing.
C	Climatic	Examples include fire damage, wind throw, frost heave, and desiccation.
D	Disease	
H	Human	
I	Insects	
U	Unknown / Not Applicable	Use this category when the reason for damage to a tree is difficult to ascertain or is not applicable.

Examples of Tree Condition codes:

Leader code
BTA – Broken Top caused by Animals

Canopy Code
BGI – Galls/Burls are present on the branches that were caused by insects

The above list only describes the damage in very general terms. Therefore, when the agent of damage can be identified in more detail, it should be noted in the comments section of the tally sheet.

7.9.10 Quality control of the field cruise

To ensure complete and correct field data collection, random quality control checks will be done. Quality control will be done at an overall level of 5%, with increased checks at the beginning of the field collection to ensure all crews are following proper procedure.

The acceptable allowable errors are as follows:

Error Type	Allowable Error
Trees in Plot	No allowable error - All trees must be correctly identified as to whether it is in the plot or not.
Tree Species	No allowable error - All tree species must be correctly identified
Tree Height and Height to live crown	A maximum of 5% of all tree heights (or height to live crown) taken, have greater than 5% error.
DBH	A maximum of 5% of all DBH should be outside +/- 1cm the true DBH.
Crown Class	A maximum of 5% incorrect crown class calls are allowed.
Age	A maximum of 5% of the tree ages are greater than +/- 3 years from the true age.
Tree Codes	A maximum of 5% error in the tree conditions codes is acceptable.
Root Collar Diameter	A maximum of 5% of root collar diameters can be greater than 5% error.
3 year growth increment	A maximum of 5% of the three-year growth increments can have greater than 5% error.

Quality control will be used both as a check for sampling errors and also to relay information to the original sampling crew to notify them of potential sampling weaknesses. During analysis this information can be used to calibrate were comparing data collected by differing crews.

7.9.11 Crew safety procedures

Crews will be expected to follow all Weyerhaeuser and Alpac safety standards while field sampling on the respective FMAs. In an attempt to minimize the chance of serious injury the following safety measures must be followed:

1. Proper safety equipment must be worn at all times (i.e. when using a chain saw or riding an ATV).
2. First aid equipment must be carried with crews at all times
3. A cell phone (or alternate form of mobile communication) will be provided to each crew.
4. Each crew will have a contact person that they will contact by 11:00 pm after every day of field work.

Procedures for phoning field contact person

1. Every evening (before 11:00 pm) a member of each crew must phone their contact person to notify them that they returned safely from the bush that day.
2. During the conversation with the contact person, a crewmember must provide an agenda for the next day. The contact person must be made aware of where the crew will be sampling the next day (they must be also be made aware of possible alternative sampling locations that potentially could be visited the next day as well). The location must be described in a way that will assist rescuers in defining the search location: legal descriptions coupled with references to permanent land features along with a bearing and distance will greatly assist in this. For example: *Tomorrow we will be in TWP 54 Rg 7 Wof5 Section 12, on a bearing of 240 °, or 150m SW from the fork in river X and river B.*
3. If the contact person has not received word from the field crew by 11:00 pm, they should try to contact the motel that the crew is staying at.
4. If the crew is not at the motel than the local RCMP should be notified of the situation. Thus, the crew must make every effort to reach the contact person if possible.
5. If a situation occurs where the crew is unable to phone the contact person prior to 11:00 pm than the crew must reach the contact at the first opportunity (not when they reach the motel room) and if the local RCMP has been contacted they must be phoned immediately as well.

7.10 Field tally sheet

Plot Information

Plot Cluster # (1)	Plot # (2)	TWP (3)	RG (4)	M (5)	Stand (6)	Date (7)	Crew (8)

Plot Measurements

Northing (1)	Easting (2)	Light Level (3)	Clear or Overcast (4)	Ecosite (5)

Overstory Species and Composition Percentage (6)	Overstory CC (7)	Understory CC (8) 0.3m	1.3m

Overstory Measurements

(1) T#	(2) Sp	(3) Ht	(5) Ht to Live Crwn	(6) DBH 1	2	(7) Crn Cls	(8) Age	(9) Def.	(10) Site Tree	(11) Comments
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										

Understory Spruce Measurements

(1) T#	(2) N/ P	(3) Hgt	(4) Ht to Live Crwn	(5) Root Dia. 1	2	(6) DBH 1	2	(7) Age 0.3m	1.3m	(8) C Cls	(9) 3yr Inc	(10) Tree Codes B	L	C	(11) Com't
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															
13															

7.11 Sample SAS analysis program for predicting WAHI

Program used for predicting WAHI in the Boreal sub-region

```
TITLE 'WAHI f (RCL-power, BAge-power, sf-quadratic)';
PROC NLIN DATA=library.filename;
      PARMS C0=0.6 C1=0.107 C2=0.8 C3=0.05 C4=0.1;
      MODEL WAHI=C0*(RCL**C1)*(Bage**C2)+C3*(sf)+C4*(sf**2);
      OUTPUT OUT=PP3 P=PREDICT R=RESID SSE=SSE;
      RUN;

PROC MEANS DATA= library.filename NOPRINT CSS;
    VAR WAHI;
    OUTPUT OUT=B3 CSS=CSS;
    RUN;

DATA _NULL_;
    SET PP3(OBS=1); SET B3(OBS=1);
    RSQ = 1 - SSE/CSS;
    FILE PRINT;
    PUT // +10 'R-SQUARE FOR THE NON-LINEAR MODEL IS DEFINED' /
           +10 'AS 1 - SSE/CSS, WHERE SSE IS THE VARIANCE OF' /
           +10 'OF THE FULL MODEL, CSS IS THE VARIANCE OF    ' /
           +10 'THE MEAN MODEL. ' //
           +10 'R-SQUARE =' +5 RSQ 8.6;
    RUN;

PROC PLOT DATA=PP3;
      PLOT WAHI*RCL;
        PLOT PREDICT*WAHI;
        PLOT RESID*PREDICT;
      PLOT RESID*WAHI / VREF=0;
      RUN;
```

7.12 Predicting WAHI for understory white spruce greater than 1.3m Tall and DBH less than 4.0 cm

wahi=C0*(RCL**C1)+(BAGE**C2)+C3*(sf)+C4*(sf**2) 31
22:53 Friday, November 15, 2002

The NLIN Procedure
Dependent Variable WAHI
Method: Gauss-Newton

Iterative Phase

Iter	C0	C1	C2	C3	C4	Sum of Squares
0	0.6000	0.1000	0.1000	0.6000	0.1000	979.2
1	-0.8910	0.4279	0.00712	0.2498	-0.3086	20.2850
2	-0.8006	-0.3287	-0.00962	0.1090	-0.1914	2.5982
3	-0.8803	-0.1068	-0.00931	0.2490	-0.3041	0.2518
4	-0.8914	-0.0895	-0.00944	0.2590	-0.3055	0.2449
5	-0.8911	-0.0900	-0.00939	0.2574	-0.3039	0.2449
6	-0.8911	-0.0900	-0.00939	0.2575	-0.3039	0.2449

NOTE: Convergence criterion met.

Estimation Summary

Method	Gauss-Newton
Iterations	6
R	3.957E-6
PPC(C2)	6.22E-6
RPC(C2)	0.000193

Object	1.534E-8
Objective	0.244919
Observations Read	668
Observations Used	291
Observations Missing	377

NOTE: An intercept was not specified for this model.

Source	DF	Sum of Squares	Mean Square	Approx F Value	Pr > F
Regression	5	2.9718	0.5944	694.04	<.0001
Residual	286	0.2449	0.000856		
Uncorrected Total	291	3.2167			
Corrected Total	290	0.7142			

The NLIN Procedure

Parameter	Approx Estimate	Std Error	Approximate 95% Confidence Limits	
C0	-0.8911	0.0118	-0.9142	-0.8679
C1	-0.0900	0.00745	-0.1047	-0.0754
C2	-0.00939	0.00258	-0.0145	-0.00431
C3	0.2575	0.0607	0.1379	0.3770
C4	-0.3039	0.0765	-0.4544	-0.1534

Approximate Correlation Matrix

	C0	C1	C2	C3	C4
C0	1.0000000	-0.5341481	-0.4400726	-0.9125643	0.8428658
C1	-0.5341481	1.0000000	-0.2785355	0.4015568	-0.3183013
C2	-0.4400726	-0.2785355	1.0000000	0.2620129	-0.2408937
C3	-0.9125643	0.4015568	0.2620129	1.0000000	-0.9807919
C4	0.8428658	-0.3183013	-0.2408937	-0.9807919	1.0000000

R-SQUARE FOR THE NON-LINEAR MODEL IS DEFINED
AS 1 - SSE/CSS, WHERE SSE IS THE VARIANCE OF
OF THE FULL MODEL, CSS IS THE VARIANCE OF
THE MEAN MODEL.

R-SQUARE = 0.798415